PB81-120081

PROCEEDINGS

Sixth National Meeting

OF THE

UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

May 1-2, 1980
University of Illinois, Urbana-Champaign

Sponsored by
National Science Foundation

Report No. UCEER-6

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

UCEER

Universities Council for
Earthquake Engineering Research
California Institute of Technology
Mail Code 104-44, Pasadena, California 91125

_AS INFORMATION RESOURCES
NATIONAL SCIENCE FOUNDATION

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-800246	2.	3. Recipient's Accession No. PB81 120081

4. Title and Subtitle
Sixth National Meeting of the Universities Council for Earthquake Engineering Research, Proceedings (May 1-2, 1980, University of Illinois, Urbana-Champaign)

5. Report Date 1980

6.

7. Author(s)
W. D. Iwan

8. Performing Organization Rept. No. UCEER-6

9. Performing Organization Name and Address
Universities Council for Earthquake Engineering Research
California Institute of Technology
Pasadena, CA 91125

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G) PFR7720044

12. Sponsoring Organization Name and Address
Engineering and Applied Science (EAS)
National Science Foundation
1800 G Street, N.W.
Washington, D.C. 20550

13. Type of Report & Period Covered
Proceedings

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)
The purpose of this meeting was to provide a vehicle for the exchange of information related to current and projected university research in earthquake engineering and to evaluate progress in specific areas of research and establish goals and priorities for future work. One hundred and sixty-seven individuals attended the meeting representing 57 universities, various government agencies, and industries. There were six topically organized sessions consisting of research reports and a summary discussion. The written summaries of these reports, along with some summaries not presented orally, are presented. The research topics were as follows: ground motion; structural elements; soils and soil-structure interaction; seismic risk, seismic design and codes; experimental structural response; and analytical structural response.

17. Document Analysis a. Descriptors
Earthquakes
Earthquake resistant structures
Earth movements
Soil dynamics
Structural engineering
Structural members
Soils

b. Identifiers/Open-Ended Terms
Earthquake Hazards Mitigation

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
NTIS	20. Security Class (This Page)	22. Price

(See ANSI–Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4–77) (Formerly NTIS–35) Department of Commerce

PROCEEDINGS

SIXTH NATIONAL MEETING

OF THE

UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

May 1-2, 1980

University of Illinois, Urbana-Champaign

Sponsored by

National Science Foundation

Report No. UCEER-6

Universities Council for Earthquake Engineering Research
California Institute of Technology
Pasadena, California 91125

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

FOREWARD

This volume contains the Proceedings of the Sixth National Meeting of the Universities Council for Earthquake Engineering Research which was held on the campus of the University of Illinois, Urbana-Champaign, May 1-2, 1980. The purpose of this meeting was to provide a vehicle for the exchange of information related to current and projected university research in earthquake engineering and to evaluate progress in specific areas of research and establish goals and priorities for future work. All university researchers with an active interest in earthquake engineering were invited to participate. Participants were encouraged to present brief oral and written summaries of their research activities or those of their particular organization.

One hundred and sixty-seven individuals attended the meeting representing 57 universities, various government agencies and industries. Travel grants were awarded to 53 individuals.

There were six topically organized sessions consisting of brief seven minute research reports and a summary discussion. Eighty individuals gave reports. The written summaries of these reports along with some summaries not presented orally are contained in this volume.

Local arrangements for the meeting were ably handled by Professor Mete Sozen and Mrs. Pat Lane of the University of Illinois. The Banquet on Thursday night at the Faculty Club was attended by 108 individuals who enjoyed the excellent food and an interesting talk on weather prediction.

Many of the details involved in the organization and execution of the meeting as well as the preparation of this volume were skillfully handled by Miss Sharon Vedrode. She well deserves a special note of appreciation.

W. D. Iwan
Executive Secretary
UCEER

TABLE OF CONTENTS

SIXTH NATIONAL MEETING
UNIVERSITIES COUNCIL FOR EARTHQUAKE ENGINEERING RESEARCH

University of Illinois, Urbana-Champaign, May 1-2, 1980

FINAL MEETING SCHEDULE

Registration/Information

April 30 - 6:00-10:00 pm - Lobby, Illini Union
May 1-2, 7:30 am - 4:30 am - Lobby, CSL Building

May 1 - CSL Auditorium

8:00 - 8:30	Opening remarks, announcements
8:30 - 9:00	Special report - Dr. Donald Senich, Director, Division of Problem Focused Research, NSF
9:00 - 10:15	Research reports and discussion - Ground Motion
10:15 - 10:45	Coffee Break
10:45 - 12:00	Research reports and discussion - Structural Elements
12:00 - 1:30	Lunch
1:30 - 2:30	Research reports - Soils and Soil Structure Interaction
2:30 - 3:00	Coffee Break
3:00 - 4:45	Research reports and discussion - Soils and Soil Structure Interaction

Conference Dinner - Levis Faculty Center

6:00 - 7:00	No host social hour
7:00 - 9:00	Dinner - Speaker: Professor Paul Handler, University of Illinois, Champaign-Urbana Title: "The Weather - Can It Be Predicted"

May 2 - CSL Auditorium

8:00 - 9:30	Research reports and discussion - Seismic Risk, Seismic Design & Codes
9:30 - 10:00	Coffee Break
10:00 - 12:00	Research reports and discussion - Structural Response, Experimental
12:00 - 1:00	Lunch
1:00 - 2:30	Research reports and discussion - Structural Response, Analytical
2:30 - 3:00	Coffee Break
3:00 - 4:45	Research reports and discussion - Structural Response, Analytical
4:45 - 5:00	Closing session

ORAL PRESENTATION SCHEDULE

GROUND MOTION

G. W. Housner, Caltech
K. Aki, MIT
G. R. Saragoni, U. Chile
J. Savy, MIT
T. C. Zsutty, Stanford
N. W. Polhemus, Princeton
P. C. Jennings, Caltech
C. J. Higgins, Higgins, Auld & Assoc.

STRUCTURAL ELEMENTS

P. Gergely, Cornell
P. J. Craig, New Jersey Inst. Tech.
S. Cherry, U. British Columbia
M. O. Porter, Iowa St.
M. Novak, U. Western Ontario
W. S. Rumman, U. Michigan
J. K. Wight, U. Michigan
S. C. Goel, U. Michigan

SOILS & SOIL-STRUCTURE INTERACTION

L.R.L. Wang, Rensselaer
W. F. Chen, Purdue
G. Gazetas, Case Western
P. A. De Alba, U. New Hampshire
O. M. El-Shafee, Wash. U.
Y. S. Chae, Rutgers
T. S. Vinson, Oregon St.
G. Ayala-Milian, VPI
J. Roesset, U. Texas
C. S. Chang, U. Mass.
G. Athanasapoulos, U. Michigan
J. H. Prevost, Princeton
A. S. Cakmak, Princeton
M. G. Sharma, Penn State
J. Penzien, Berkeley
D. A-Grivas, Rensselaer
W. J. Hall, U. Illinois
Y-H. Pao, Cornell
T. Ariman, Notre Dame

SEISMIC RISK, SEISMIC DESIGN & CODES

M. Fintel, Portland Cement Assoc.
D. A. Gasparini, Case Western
R. W. Stephenson, U. Missouri
A. H-S. Ang, U. Illinois
A. Haldar, Georgia Inst. Tech.
T. E. Blejwas, Okla. State U.
R. L. Sharpe, ATC
W. G. Milne, Pacific Geoscience Ctr.
A. S. Kiremidjian, Stanford
F. Y. Cheng, U. Missouri

STRUCTURAL RESPONSE, EXPERIMENTAL

E. P. Popov, Berkeley
B. M. Douglas, U. Nevada, Reno
J. M. Plecnik, Cal State Long Beach
W. G. Godden, Berkeley
A. E. Aktan, Berkeley
H. Krawinkler, Stanford
H. E. Lindberg, SRI
D. Rea, UCLA
G. Hart, UCLA
J. P. Moehle, U. Illinois
A. Schiff, Purdue
F. Udwadia, USC
S. Mahin, Berkeley

STRUCTURAL RESPONSE, ANALYTICAL

M. P. Singh, VPI
J.T.P. Yao, Purdue
J. N. Yang, George Wash. U.
A. K. Chopra, Berkeley
M. A. Haroun, Caltech
M. Saiidi, U. Nevada, Reno
C. N. Kostem, Lehigh
J. F. Abel, Cornell
C. Meyer, Columbia
Y. K. Wen, U. Illinois
P. Mueller, MIT
W. D. Iwan, Caltech
P. Spanos, U. Texas
Y. K. Lin, U. Illinois
R. K. Miller, USC
D. V. Reddy, Florida Atlantic U.
W. O. Keightley, Montana St.
A. A. Huckelbridge, Case Western
B. J. Goodno, Georgia Inst. Tech.
A. M. Abdel-Ghaffar, Princeton
W. A. Mash, U. Massachusetts
F. W. Barton, U. Virginia

Note: The schedule of oral presentations does not necessarily correspond to the schedule of written summaries. See the Index of Authors of Written Summaries, pages 271-272, for a complete listing of individuals submitting written summaries.

ATTENDANCE LIST

Abdel-Ghaffar, A. M.	Princeton
Abedi, M. H.	University of Illinois, Urbana
Abel, J. F.	Cornell
A-Grivas, D.	Rensselaer
Aki, K.	MIT
Aktan, A. E.	Berkeley
Aktan, Haluk	Wayne State
Algan, B.	University of Illinois, Urbana
Ang, A. H-S.	University of Illinois, Urbana
Ariman, T.	Notre Dame
Astaneh, Abolhassan	University of Michigan
Athanasopoulos, G. A.	University of Michigan
Ayala-Milian, G.	Virginia Polytechnic Institute
Babcock, C. D.	Caltech
Babendreier, C. D.	NSF
Barton, F. W.	University of Virginia
Bergman, L. A.	University of Illinois, Urbana
Blejwas, T. E.	Oklahoma State University
Bruce, J. R.	SRI International
Cakmak, A. S.	Princeton
Cevallos, P. J.	Illinois Institute of Technology
Chae, Y. S.	Rutgers
Chang, Cheng-Jung	Purdue
Chang, C. S.	University of Massachusetts
Chang, N-Y.	University of Colorado, Denver
Chen, W. F.	Purdue
Cheng, F. Y.	University of Missouri, Rolla
Cherry, S.	University of British Columbia
Chopra, A. K.	Berkeley
Costello, G.	University of Illinois, Urbana
Cotran, F. S.	University of Illinoil, Urbana
Chu, Peter	Purdue
Craig, R. J.	New Jersey Institute of Technology
Craig, J. I.	Georgia Institute of Technology
Dasgupta, G.	Columbia
De Alba, P. A.	University of New Hampshire
Dikmen, U.	University of Illinois, Urbana
Dimarogonas, P.	Purdue
Douglas, B. M.	University of Nevada, Reno
Drenick, R. F.	Polytechnic Institute of New York
Durrani, A.	University of Michigan
El-Shafee, O. M.	Washington University

ATTENDANCE LIST (CONTINUED)

Fajfar, P.	University of Ljubljana
Fintel, M.	Portland Cement Association
Foutch, D. A.	University of Illinois, Urbana
Fujino, Y.	University of Illinois, Urbana
Fuh, Jon-shen	University of Illinois, Urbana
Gasparini, D. A.	Case Western Reserve
Gaus, M. P.	NSF
Gazetas, G.	Case Western Reserve
Gergely, P.	Cornell
Ghosh, S. K.	Portland Cement Association
Gilbertsen, N.	University of Illinois, Urbana
Godden, W. G.	Berkeley
Goel, S. C.	University of Michigan
Goodno, B. J.	Georgia Institute of Technology
Gugerli, H.	University of Michigan
Gupta, A. K.	Illinois Institute of Technology
Hanson, R. D.	University of Michigan
Haldar, A.	Georgia Institute of Technology
Hall, W. J.	University of Illinois, Urbana
Hariandja, B.	University of Illinois, Urbana
Haroun, M. A.	Caltech
Hart, G. C.	UCLA
Higgins, N.	Higgins, Auld & Associates
Hoedajanto, D.	University of Illinois, Urbana
Housner, G. W.	Caltech
Hsiung, G. S.	Washington, D.C.
Hsiung, P.	Washington, D.C.
Hsieh, B. J.	Argonne National Lab
Hu, Y.	Berkeley
Huckelbridge, A. A.	Case Western Reserve
Israelson, O. A.	National Academy of Sciences
Iwan, W. D.	Caltech
Jennings, P. C.	Caltech
Jones, Lindsay	Computech
Kamel, A.	Purdue
Keightley, W. O.	Montana State
Kesler, C.	University of Illinois, Urbana
Khachaturian, N.	University of Illinois, Urbana
Kim, B. J.	Purdue
Kiremidjian, A. S.	Stanford
Kirkner, D. J.	Notre Dame

ATTENDANCE LIST (CONTINUED)

Koizumi, T.	Purdue
Kostem, C. N.	Lehigh
Krauthammer, T.	University of Illinois, Urbana
Krawinkler, H.	Stanford
Kreger, M.	University of Illinois, Urbana
Kung, S-Y.	University of Illinois, Urbana
Lauda, R.	NSF
Lee, B-J.	Washington University
Lin, Y. K.	University of Illinois, Urbana
Lindberg, H. E.	SRI International
Liou, M-T.	University of Illinois, Urbana
Liu, H. H.	Purdue
Liu, Xuixian	Institute of Engr. Mech., Harbin
Luo, Xuihai	Institute of Engr. Mech., Harbin
Mahin, S. A.	Berkeley
Mayes, R.	Applied Technology Council
McGuire, W.	Cornell
Meyer, C.	Columbia
Miller, R. K.	USC
Milne, W. G.	Pacific Geoscience Center
Moehle, J.	University of Illinois, Urbana
Morrison, D.	University of Illinois, Urbana
Mueller, P.	MIT
Murtha, J. P.	University of Illinois, Urbana
Nash. W. A.	University of Massachusetts
Nematollaahi, K.	Purdue
Newmark, N. M.	University of Illinois, Urbana
Novak, M.	University of Western Ontario
Pao, Y-H.	Cornell
Park, R.	University of Canterbury
Pearce, H.	University of Illinois, Urbana
Pecknold, D. A.	University of Illinois, Urbana
Penzien, J.	Berkeley
Plecnik, J. M.	Cal State, Long Beach
Polhemus, N. W.	Princeton
Popov, E. P.	Berkeley
Porter, M. L.	Iowa State University
Prevost, J. H.	Princeton
Radziminski, J. B.	University of South Carolina
Rahder, M.	University of Illinois, Urbana
Rea, D.	UCLA
Reddy, D. V.	Florida Atlantic University

ATTENDANCE LIST (CONTINUED)

Reseidat, M. R.	Purdue
Richart, F. E.	University of Michigan
Roesset, J.	University of Texas, Austin
Rumman, W. S.	University of Michigan
Safak, E.	University of Illinois, Urbana
Saiidi, M.	University of Nevada, Reno
Santiago, J.	University of Michigan
Saragoni, G. R.	University of Chile
Savy, J.	MIT
Scalzi, J. B.	NSF
Schiff, A. J.	Purdue
Schnobrich, W. C.	University of Illinois, Urbana
Scribner, C. F.	University of Illinois, Urbana
Senich, D.	NSF
Shah, S. D.	Purdue
Sharma, M. G.	Penn State
Sharpe, R. L.	Applied Technology Council
Shih, T-Y.	University of Illinois, Urbana
Shye, K-Y.	University of Illinois, Urbana
Singh, M. P.	Virginia Polytechnic Institute
Sozen, M. A.	University of Illinois, Urbana
Spanos, P-T. D.	University of Texas, Austin
Stephenson, R. W.	University of Missouri, Rolla
Stepneski, A.	University of Illinois, Urbana
Sunidja, H.	University of Illinois, Urbana
Tang, W. H.	University of Illinois, Urbana
Toussi, S.	Purdue
Tzou, H-S.	Purdue
Udwadia, F. E.	USC
Vasilescu, D.	University of Illinois, Urbana
Vasseghi, M.	University of Illinois, Urbana
Veletsos, A. S.	Rice University
Vinson, T. S.	Oregon State University
Walker, W. H.	University of Illinois, Urbana
Wang, L.R.L.	Rensselaer
Wen, Y.	University of Illinois, Urbana
White, R. N.	Cornell
Wight, J. K.	University of Michigan
Wood, R.	University of Michigan
Wu, S-M.	University of Michigan

ATTENDANCE LIST (CONCLUDED)

Yamamoto, Masaaki	University of Illinois, Urbana
Yang, J. N.	George Washington University
Yao, J.T.P.	Purdue
Zsutty, T. C.	Stanford

WRITTEN RESEARCH SUMMARIES

The following research summaries are arranged by subject area as specified by the author(s). Within a given subject area, summaries are arranged alphabetically by institution and author. For a complete index of authors of written summaries, see pages 271-272.

GROUND MOTION

AJIT K. MAL

University of California, Los Angeles

The major ultimate objective of all ground motion research is to provide in advance, the motion expected to occur at a given site in future earthquakes. Due to highly complex nature of the earthquake phenomenon only limited aspects of this objective can be realized. Our research has been focused on the characterization and eventual prediction of strong ground motion for engineering applications. Our approach has been based on the premise that the geologic structure in the vicinity of the site including major faults and soil conditions, is known.

In recent years, several research groups have developed computer codes that generate theoretical ground motion time histories for models in which the earthquake source is represented by a distribution of double couples and the earth by a flat multilayered elastic continuum. The models for these calculations have been developed on the basis of knowledge derived largely from far field seismological observations or near field (static) geodetic observations. The frequencies and/or distances in these observations are usually outside the ranges of interest in engineering applications. Clearly, many of the source properties (e.g., abrupt change in propagation velocity) and layer properties (e.g., rapid variation in near surface shear wave speed), ignored in seismological models may be more significant at high frequencies.

Our most recent research has been directed toward identifying those features in models of the source and the earth that are most effective in generating strong high frequency ground motion. The influence of the source was examined by placing complex faultings in a simple (uniform half space) model of the earth. A two dimensional (in plane) model was used for dip slip type faults and three dimensional model for strike-slip faults. The influence of layering was examined by placing a point dislocation in a multilayered earth model. The problem was formulated in the frequency domain; body and surface wave spectra were calculated separately. Time histories were obtained by means of an FFT algorithm. Details of the formulation can be found in Duke and Mal (1978). Some of our recent results are as follows:

1. The most significant high frequency motion from a rupture that suddenly appears on a fault at depth and subsequently propagates with constant velocity is a single shear pulse. An abrupt change in rupture velocity (including change of direction or stoppage) introduces a second shear pulse, which may (or may not) be significant.

2. For a dip-slip or thrust type surface faulting the significant ground motion is a single Rayleigh pulse. The same is true for a propagating strike slip type surface faulting: the sharpness of the Rayleigh pulse depends on the rupture speed and length of faulting.

3. For buried sources in a multilayered medium the ground motion is not

significantly sensitive to moderate variations in source depth and eipcentral distance.

4. Calculated spectra from theoretical models with only material damping (i.e., viscoelasticity) have significantly slower decay with frequency than those calculated from the available near field accelerogram. Inclusion of some loss mechanism at the source (e.g., friction) is essential for near field calculations.

In conclusion, our research indicates the need to create models of the earthquake source that differ from existing seismological models. The engineering model of the source must include features that are most effective in generating high frequency motion but may ignore others that are effective in producing long period waves. Clearly, it is also necessary to create similar engineering models of the earth which may include a top layer of varying elastic properties overlying others having uniform properties.

REFERENCES

1. Duke, C. M. and Mal, A. K., "Site and Source Effects on Earthquake Ground Motion", School of Engineering and Applied Science, University of California, Los Angeles, Res. Rep. UCLA - ENG - 7890, Nov. 1978.

G. RODOLFO SARAGONI

University of Chile

University of Chile has been conducting the research project on "Destructiviness of Earthquake Ground Motions".

The fields under study are capacity of strong motion to cause damage to structures, installation of strong motion accelerographs, theoretical and empirical characterization of earthquake ground motion.

1. Capacity of Strong Ground Motions to Cause Structural Damages.

An attempt to identify strong motion parameters that control ductility requirements for simple nonlinear structures has been done. Expected ductility requirements for simple elastoplastic and stiffness degrading structures are studied in terms of expected maximun ground acceleration, duration of strong motion region and characteristic frequency or intensity of zero corossings as earthquake accelerogram parameters and natural period and damping as structural parameters.

The solution to this problem could explain large differences in structural damage observed during strong earthquakes. This study is of particular interest when structural responses due to accelerograms generated at subduction seismic zones (Alaska, Chile and Japan) are compared with the ones produced at transcursive seismic zones as California and Central América.

Estimation of simple elastoplastic oscillator expected ductility required under action of nonstationary acceleration process $\{a(t)\}$ is done by using the approximated solution of the Fokker-Plank equation for random responses of hysteretic structures with strong nonlinearity suggested by Sveshnikov (1) and adapted by Kobori et al. (2). This method considers the transformation of the equation for probability density function to the equation for the characteristic function and the expansion of characteristic function in terms of power series when the nonlinear hysteretic characteristics are expressed by a signum type function of state variables.

It is concluded (3) that earthquake ground motion destructiviness associated to expected ductility requirement of simple elastoplastic oscillator dependes essentially of expected maximum ground acceleration and intensity of zero crossings acting both parameters always simultaneously.

The results obtained are particularly important when accelerogram recorded in transcursive and subductive zones are compared. Since subductive earthquake accelerograms usually have larger values of intensity of zero crossings than transcursive ones it can be expected in these zones to record accelerograms with very large maximum ground acceleration that does not produce structural damage. In this are maximum ground acceleration must be connected to the intensity of zero crossings effect and use and smaller value of expected maximum ground acceleration or effective ground acceleration.

Strong motion duration can duplicate ductility requirements. However its influence can be considered secondary compare with effects of expected maximum ground acceleration and intensity of zero crossings.

Figs. 1, 2 and 3 show the influence of expected maximum ground acceleration $E\{a_{max}\}$, duration of strong motion region Δt_s and intensity of crossings ν_0 on the expected ductility requirements of elastoplastic oscillators.

2. Installation of Strong Motion Accelerographs.

The installation of 10 new accelerographs in the Valparaíso-La Ligua-Santiago region was done in 1979. With this new array is expected to record in the next ten years an event of magnitude 8.5 with epicenter at the sea in front of Valparaíso and other of magnitude 7.5 with epicenter near La Ligua.

With the Organization of American States project "Andean Seismic Protection" the accelerograph-national network will be expand from 37 to 57. Ten of the new 20 instruments were already bought and they will be located at the same region in order to increase the reliability of the network in this area and the probability to obtain records at epicentral regions or populated areas.

3. Characterization of Earthquake Accelerograms.

Three gaussian properties of earthquake accelerograms were derived using the central limit theorem (4). The properties are:

i) mean square acceleration tends to a chi-square function.

ii) probability density function of acceleration amplitudes is gaussian with zero mean and mean square value variable in time, given by the chi-square function, and

iii) generalized autocorrelation function tends to a gaussian function in the vecinity of the origin.

Two first properties were satisfactory verified to a 1% level of significance by application of run and chi-square tests to a set of 16 accelerograms from U.S.A., Chile and Argentina. The third property has satisfactory verified by simple comparison with realized functions.

4. References.

1. Sveshnikov, A. A. "Application of the Theory of Continuous Markov Processes to the Solution of Nonlinear Problems of Applied Gyroscopy". Proc. S. Int. Conf. Nonlinear Oscillations, Vol.3, (1970).
2. Kobori, T., R. Minai and K. Asano "Random Response of the Nonlinear System with Hysteretic Characteristics". Proceedings, 24 th. Japan Nat. Congress for App. Mechanics, Tokyo, Japan, 1974.
3. Araya, R. and G.R. Saragoni "Capacity of Strong Ground Motion to Cause Structural Damage", 7 WCEE, Istambul, Turkey, 1980.
4. Saragoni, G.R., R. Alarcón and J. Crempien "Gaussian Properties of Earthquake Ground Motion", 7 WCEE, Istambul, Turkey, 1980.

Reproduced from best available copy.

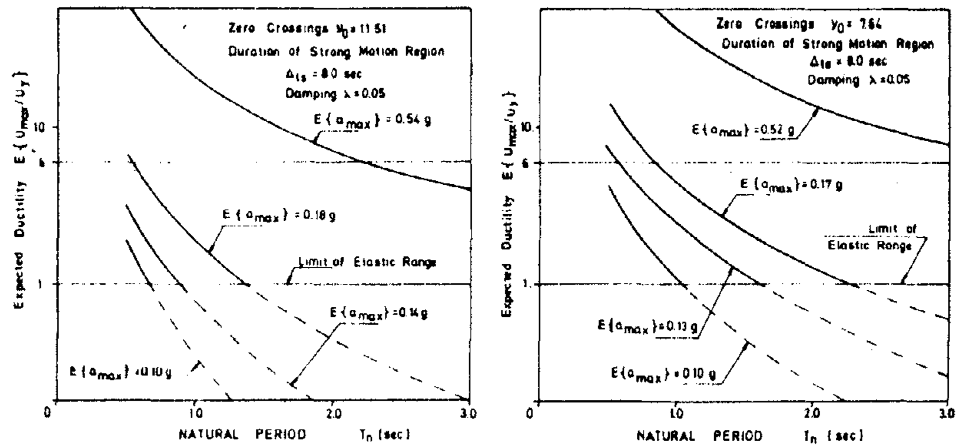


Fig. 1 INFLUENCE OF EXPECTED MAXIMUM ACCELERATION E { a_{max} } ON EXPECTED DUCTILITY

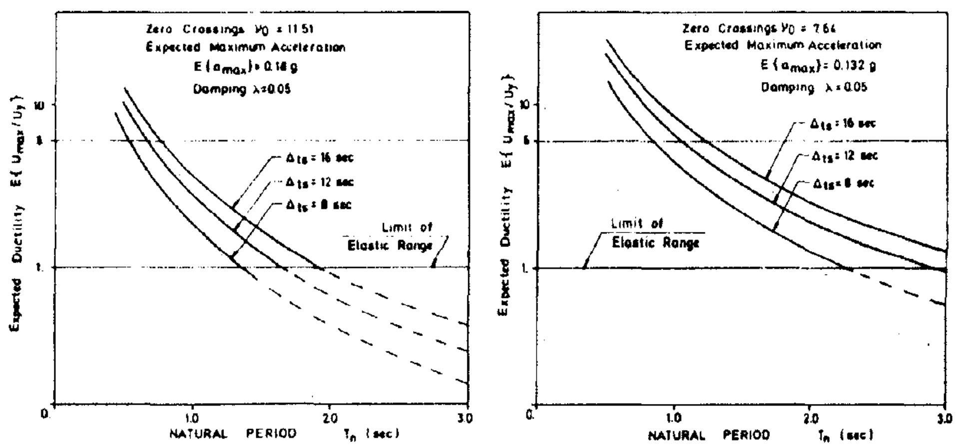


Fig. 2 INFLUENCE OF DURATION OF STRONG MOTION REGION Δ_{ts} ON EXPECTED DUCTILITY

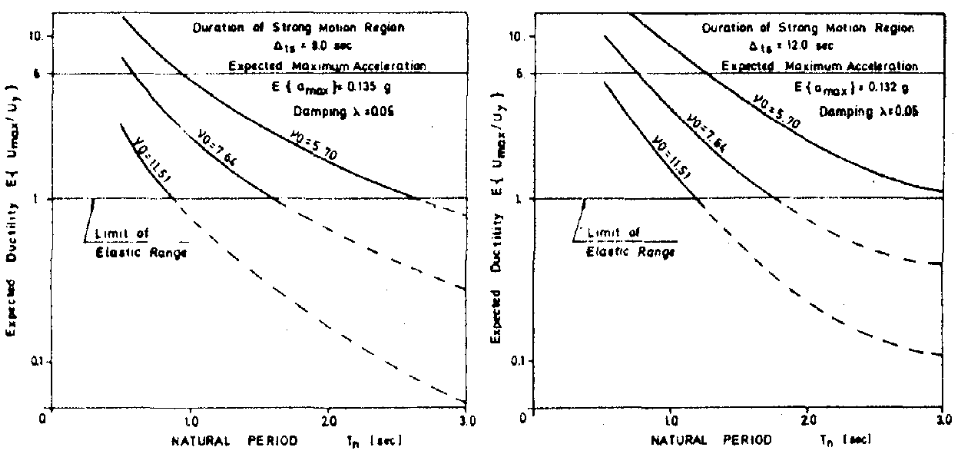


Fig. 3 INFLUENCE OF ZERO CROSSINGS OR CHARACTERISTIC FREQUENCY ON EXPECTED DUCTILITY

COMPILED BY J. HEALEY

Cornell University

The followin is a brief account of the various research projects concerned with seismology in the Department of Geological Sciences.

Search for Precursors to Earthquakes in the New Hebrides Island Arc by Monitoring Tilt and Seismicity (B. Isacks; USGS)

Observations taken close to the plate boundary of a seismically active subduction zone include (1) recordings of tilt by a network of borehole, bubble-level tiltmeters, by a long-baseline water-tube tiltmeter, and by releveling of two arrays of benchmarks; and (2) monitoring of locations of small earthquakes by a network of seismographs. Precursors to large earthquakes are sought in the measurements of tilt and in the temporal variations of the locations and source properties of numerous small earthquakes. Although no earthquakes with magnitudes larger than 5 1/2 have occurred in the region covered by the observations, the past seismicity record indicates that larger events are due.

Regional Seismic Wave Propagation (B. Isacks and J. Oliver, AFOSR)

The objective of this program is to compile a global reference catalog for seismic wave propagation at regional distances. Hundreds of short-period WWSSN seismograms are being examined visually in an effort to map lateral variations in wave propagations across an area. The first region studied is the Middle East, with Tibet and adjacent regions of Central Asia to follow. Emphasis is placed, in particular, on a study of the variations in propagation of the high-frequency shear waves Sn and Lg. Studies of other areas will be compared with that of the Middle East.

Stress State in the Lithosphere (D. L. Turcotte; NSF)

The primary focus is on sedimentary basins and major strike-slip faults. Both the mechanisms of basin formation and the structure of basins are studied. The similarity solution for basin subsidence derived is applied to a variety of basins, and basins whose structure appears to be dominated by flexure are studied in detail. Examples include the Appalachian and Hudsons Bay basins. Mechanisms of stress accumulation and release on major strike-slip faults are also studied. The role of frictional heating and temperature-dependent rheologies on the cyclic faulting system is receiving particular attention.

Geological Processes along the San Andreas Fault (D. L. Turcotte and F. H. Kulhawy; NASA)

The three-dimensional strain field adjacent to the San Andreas fault is studied using the finite element method. The distribution of surface strain and stress between great earthquakes will be obtained and will be compared with available geodetic measurements. The results will be particularly important in determining the sites for geodetic stations to monitor the cyclic strain history of the fault.

Study of the Excitation of the Seismic Phases Pn, Sn, and T produced by Earthquakes Located Along the New Hebrides Island Arc and Recorded at Stations Located Seaward of the Arc (J. Oliver and B. Isacks; ONR)

Ocean bottom seismic data and land seismograms are analyzed to develop a synthetic seismogram computer program to determine focal depths of shallow oceanic earthquakes. A digital seismograph network has been intalled on the Loyalty Islands to record the seismic phases Pn, Sn, and T from earthquakes in New Hebrides. The nature of the offshore-onshore propagation of T as recorded by land stations is specifically investigated. The data are analyzed in terms of apparent velocities (or phase velocities) and particle motions of the recorded waves, and thus information about the mode of propagation of T as well as that of Pn and Sn are obtained.

Seismotectonics of Subduction Zone: Intensive Field Studies of the New Hebrides Island Arc Complemented by Comparative Studies of Other Zones of Lithosphere Subduction (B. Isacks; NSF)

New observations are sought by (1) intensive studies of detailed structure and seismicity of the New Hebrides island arc and (2) comparative studies of other zones of subduction through analysis of teleseismic data. The New Hebrides work will focus on data from a new seismograph network established in the region that covers the shallow part of the subduction zone and continued analysis of data from the global networks and temporary networks previously operated in the region. Detailed resolution of the structure and seismicity is likely to produce new insights into the mechanics of subduction, the generation of large earthquakes, and the causes of island arc volcanism. The studies of other subduction zones based on global data will include determinations of three-dimensonal configuration of Benioff zones and the relationship to regional tectonic processes, deformation of the descending lithosphere, and convective flow of material in the mantle; determinations of thickness, detailed structure and focal mechanisms in mantle seismic zones; and studies of shallow seismicity above the subducted plate, especially in the region of western South America, where important modern analogues exist for Laramide-type orogenic activity.

Study of Hazards Related to the Suva-Mbengga Seismic Zone in Fiji (B. Isacks; AID)

A seismically active fault zone that may run through the City of Suva was discovered by previous Cornell work in Fiji. The exact location of this fault zone has immense implications; building codes must be studied and town plans revised, and microzoning is vital. Steps to minimize the impact of any strong earthquakes through proper planning procedures must be taken. Since 1953 4 strong earthquakes were felt in Suva and one mag. 6.75 earthquake caused considerable damage and resulted in 8 casualties in Suva and Kandava. Cornell is assisting the Fiji Mineral Resources Division, which has primary responsibility for the project, to acquire and install the required instrumentation and will provide technical help in the analysis of data.

Seismic Reflection Profiling to Determine Fine Structure of the Crust and Upper Mantle (J. Oliver, S. Kaufman, and L. Brown; NSF)

Application of modern high-resolution seismic profiling methods of the petroleum industry to studies of the continental crust and upper mantle. The sites successfully surveyed to date in the U.S. are Hardeman County, TX; the Rio Grande Rift, N.M.; Coalinga and Parkfield, CA; Abo Pass, N.M.; Wind River Uplift, WY; Anadarko Basin, OK; Charleston, S.C.; Michigan Basin, Kansas MGA; Minnesota Precambrian; and a traverse in the Southern Appalachians. Further work in the Souterh Appalachians, as well as in other sites, is projected.

Fine Structure of the Crust and Upper Mantle from Analysis of Seismic Reflection Records (J. Oliver, S. Kaufman, and L. Brown; NSF)

This investigation makes comparative analyses of seismic reflection profiling data from sites profiled by COCORP. Syntheses of the data thus far have been primarily qualitative, i.e., visual identification and mapping of similar and dissimilar characteristics of reflector patterns in the deep crust. Recent installation of a new dedicated computer will accelerate this research.

Recent Vertical Movements of the Crust in the Western U.S. (USGS) and Recent Vertical Crustal Movements: The Eastern United States (NRC) (J. Oliver and L. Brown)

Vertical crustal movement information derived from releveling data collected by the NGS in the western U.S. is used to determine to what extent this data base can contribute to our understanding of geodynamic phenomena with emphasis on earthquake prediction and seismic hazard evaluation. In the eastern U.S., integration of precise leveling data and results from independent methods of determining elevation changes are used to study the intraplate regions. Research includes analysis of a map of vertical crustal movements produced for the East; preparation of a grid of geodetic observations in the southern states, including Texas, Louisiana, and Mississippi, investigation of relative arching in the Gulf Coast, development of methods of geomorphic analysis for identifying crustal movements; and analysis of possible elevation-correlated leveling errors in releveling results. Leveling results are interpreted in view of other relevant geophysical and geological data.

Precise Leveling, Space Geodesy, and Geodynamics (J. Oliver and L. Brown; NASA)

Vertical crustal movement information, derived from repeated leveling surveys, is used to determine stable areas where space-based systems can be tested, locate presently active areas where space systems are most likely to detect tectonic deformation, and determine the precision and frequency of measurements necessary to monitor crustal movements in different areas. Leveling results will also be used to evaluate the precision of space techniques and to integrate leveling results with space-based measurements of crustal movement to enhance our understanding of contemporary crustal dynamics.

CORNELIUS J. HIGGINS

Higgins, Auld & Associates, Inc.

This paper summarizes recent and current research in the use of high explosives to simulate earthquake ground motion effects on engineering systems. This research is being pursued because of the need for response data on large structures in general and on soil and soil-structure systems which cannot be evaluated adequately in any other way. The research discussed was performed primarily at the University of New Mexico and at the author's current firm.

Recent studies by the University of New Mexico for the National Science Foundation (NSF) (Ref. 1) and the Electric Power Research Institute (EPRI) (Refs. 2 and 3) have indicated that it is technically and economically feasible to simulate earthquake-like ground motions with high explosives. The NSF study involved analysis of high explosive field data from experiments performed prior to about 1977, and finite difference calculations of various explosive configurations to derive prediction relations in dry alluvium that could be used in simulation designs. The explosive charge configurations considered were spherical, cylindrical and planar. The planar array configuration was determined to be most adaptable to simulation because it provides relatively uniform motions across the width of the array and, in addition, allows a wider range of control over motion amplitudes and attenuation rates than is possible with concentrated charges.

The NSF study also included consideration of a number of other factors in simulation design. These included scaling to other geologies, enhancement techniques and simulation criteria. In the area of scaling to other geologies, dimensional analysis and a few elastic calculations were used to derive relations for extrapolating in elastic materials. With regard to simulation techniques, it was recognized that it might be necessary in some simulations to enhance the ground motions produced by explosions to improve their fidelity compared with earthquake motions. Enhancements evaluated included methods for increasing the number of motion cycles and the duration of excitation; methods for reducing the frequency of the motion; and methods for reducing the peak acceleration while maintaining relatively high levels of particle velocity and displacement.

The use of multiple, sequenced explosions appeared to be a viable method for enhancing numbers of cycles and durations. This was amply demonstrated by the later EPRI experiments. A potential method for reducing the frequency content of the explosive ground motion was decoupling of the explosion by detonating in cavities. A potential method for reducing accelerations while maintaining relatively high levels of velocity and displacement was identified as the use of trench shields.

The NSF study also looked briefly at simulation criteria. Since every feature of an earthquake cannot be reproduced in detail, it was recommended that simulation criteria be based upon system response to credible earthquake-like motions. The simulation should be designed to excite the types and amplitudes of response that might be expected in a strong earthquake rather than to reproduce every specific earthquake detail. Response spectra were recommended as one means of evaluating response and establishing criteria.

The NSF study was used as the main basis for the design of the SIMQUAKE series of tests (Refs. 2 and 3). These tests, conducted at the McCormick Ranch Test Site of the University of New Mexico, were designed to simulate strong earthquake ground motion effects on model nuclear power plant structures. The largest experiment was SIMQUAKE II, a double array experiment. The experiment involved two large explosive arrays with approximately 30 tons and 40 tons of ANFO, respectively, in the front and back arrays. The back array was fired first and the front array was fired 1.2 seconds later. Six (6) model structures were included in the test and 144 active measurements were made. Parameters investigated included structure scale, depth of embedment, backfill type, and level of ground motion excitation.

The studies cited demonstrated technical and economic feasibility of explosive simulation, provided data on generic nuclear power plant structures, and suggested areas where further investigation can lead to additional progress in simulation technology. The current NSF program at Higgins, Auld & Associates, Inc. (HA&A) is addressed to the improvement of simulation capability. Research is underway in four areas:

- The update of simulation prediction methods based upon a synthesis of recently obtained simulation field data with the current prediction methods.

- The development of simulation design prediction methods for a wider range of geologies.

- The further investigation of enhancement methods. In particular, the use of trench shields to reduce the acceleration transmitted to a test area while maintaining relatively high levels of velocity and displacement.

- The development of simulation criteria and simulation designs for a few selected generic engineering systems.

The major source of directly applicable data is the SIMQUAKE series of tests performed by the University of New Mexico. The series consisted of four events: Mini-SIMQUAKE, SIMQUAKE IA, SIMQUAKE IB and SIMQUAKE II. These were the first set of explosive experiments designed expressly for earthquake simulation purposes. Over 375 channels of data were recorded of which about 50 percent were free-field ground motion response measurements.

The SIMQUAKE ground motion data is being analyzed and synthesized with the data presented and analyzed in Reference 1. The SIMQUAKE data will be used to help in answering simulation questions associated with the wave structure of the explosive experiments, the ratio of vertical to horizontal motions in the explosions and the ground motion frequency prediction methods.

Data measured at SRI International also forms an important part of the current simulation data base. The data on source coupling will be compared with the source coupling calculations of Reference 1. In addition, these experiments provide additional data on the effect of array size. The geologies for the SRI experiments are somewhat different than McCormick Ranch. Some insight into geology difference effects may also be obtained from the data.

The effect of geology is very important in simulation design. Almost all data now available are in dry alluvium. Yet simulation procedures must be developed for a wide range of geologies. Wet geologies are of particular concern because of the possibility of cyclic mobility or liquefaction. Prediction methods which are applicable in any geology are being developed. Since the amount of data in varying geologies are limited, the major work here is through the use of finite difference calculations.

Analysis of the use of trench shields to modify the motions entering a test area is also being analyzed primarily with finite difference calculations. It is necessary to consider variations in the size and loading density of the explosive array, the range to the test area, and material properties, as well as the trench depth.

It is believed that at the conclusion of the research currently in progress, it will be possible to go to the field to actually test large scale engineering systems. As the last part of the HA&A study, simulation requirements for selected engineering systems will be evaluated, and preliminary simulation designs will be developed. The actual systems to be evaluated will be selected during the research after consultation with NSF and others in the earthquake community. Candidate systems include masonry structures, underground pipelines, tunnels, bridge abutments, earth dams, retaining walls and POL storage tanks, to name a few.

References

1. Higgins, C. J., Johnson, R. L. and Triandafilidis, G. E., The Simulation of Earthquake-Like Ground Motions with High Explosives, Report No. CE-45(78)NSF-507-1 on NSF Grant ENG 75-21580, The University of New Mexico, Albuquerque, New Mexico, July 1978.

2. Higgins, C. J., et al, SIMQUAKE I- An Explosive Test Series Designed to Simulate the Effects of Earthquake-Like Ground Motions on Nuclear Power Plant Models, 7 Volumes, University of New Mexico Report on Contract RP 810-1 for the Electric Power Research Institute, Palo Alto, California, January 1979.

3. Higgins, C. J., Simmons, K. B. and Pickett, S. F., SIMQUAKE II - A Multiple Detonation Explosive Test to Simulate the Effects of Earthquake-Like Ground Motions on Nuclear Power Plant Models, 8 Volumes, University of New Mexico Report on Contract RP 810-1 for the Electric Power Research Institute, Palo Alto, California, January 1979.

M. Ö. ERDİK

Earthquake Engineering Research Institute
Middle East Technical University

The determination of site effects to be reflected in the new Turkish Earthquake Resistant Design Code are being pursued under the sponsorship of the Earthquake Research Institute. The work (1) the collection and evaluation of the observed site effects from the macroseismic data files on Turkish Earthquakes and, in parallell, (2) the development of simple theoretical models to predict the controlling parameters of soil amplification. These studies will be correlated to provide a simple, yet realistic procedure to account for site effects in earthquake resistant design. The uniformity and homogenity of Turkish rural housing and settlements provide a good opportunity to assess the degree of local variations in the intensity of ground motion from the observed earthquake damage inventories.

This paper outlines the development and applications of a simple, analogous single-degree-of-freedom (SDF) model for the non-linear soil amplification. The development is based on the assumption that the response of the soil deposit over the bedrock is mainly due to the upward propagation of horizontally polarized shear waves. The soil deposit is assumed to have constitutive relations of the Ramberg-Osgood type with a maximum shear stress, varying linearly with depth, and a low-strain shear modulus, varying lineary with the square root of the depth.

The Analogous SDF Model

An analogous, nonlinear-hysteretic, SDF model representing the first mode response characteristics of the actual soil deposit can be derived: (1) by setting the frequency of vibration of the SDF model equal to the fundamental frequency of vibration of the soil layer and, (2) by insuring that the amount of energy dissipated per cycle by the SDF model is equal to that dissipated by the soil deposit responding in its fundamental mode, for all strain levels. Here, it should be noted that, the terms of frequency and mode are being used rather loosely, and they actually refer to their strain dependent apparent values. It has been shown that (Erdik, 1979) such a SDF model will have a frequency of vibration, f, given by:

$$f = f_1[1/(1 + 1.07\ u/U_r)]^{\frac{1}{2}} \qquad [1]$$

and a nonlinear-hysteretic spring with constitutive characteristics given by:

$$F = \frac{u/U_r}{1+1.07|u/U_r|} \quad \text{and} \quad F = \frac{2u/U_r}{2+1.07|u/U_r|} \qquad [2,3]$$

respectively for the initial loading and unloading or reloading paths. It has also been assessed that, if f_1 of Eqn.1 is set equal to the fundamental frequency of the soil layer and, U_r, termed reference displacement, is taken to be the value obtained by integration of the 'reference strain' (After, Hardin and Drnevich, 1972) throughout the depth of the soil layer, than the deformation, u, of the SDF model will be analogous to the surface displacement of the soil deposit.

Assessment of the Accuracy and Parametric Studies

The approximation provided by this analogy is tested for the following two cases. The first case involves the response of a 200 m deep soil deposit to the N21E component of 7.21.1952 Taft record scaled to a peak acceleration of 0.7g. The surface velocity as given by Joyner and Chen (1975), and as obtained on the basis of the analogous SDF model, with f_1 = 0.5 Hz. and U_r = 22.7cm, are provided in Fig.1. The second test case involves the response of the 50ft. deep soil deposit to the SOOE component of El-Centro record scaled to a peak acceleration of 0.1g. The surface velocity as given by Martin and Seed (1978), and as obtained on the basis of the analogous SDF model, with f_1 = 3.1 Hz. and U_r = 1.1cm, are provided in Fig.2. Both of these comparisons indicate the excellent approximation provided by the analogous SDF model.

Parametric studies conducted using 12 different accelerograms as the bedrock motion (to be presented in 7.WCEE) have resulted in the iso-amplification contour envelopes given in Fig.3 for different peak bedrock velocity and accelerations. The ranges of the reference displacement in the vertical axis and the fundamental frequency of vibration in the horizontal axis covers a wide group of soil deposits of importance in earthquake engineering. It can be assessed that: (1) for a given soil deposit the greater the intensity of bedrock motion smaller is the acceleration, (2) for a given soil deposit and bedrock motion the velocity amplification is greater than that of acceleration, (3) for peak bedrock velocities greater than 20 cm/sec. the amplification is always less than two, (4) for peak bedrock accelerations greater than 0.2g the amplification is always less than 1.5 and the bedrock accelerations with peaks above 0.5g are de-amplified. Note that, in general the ATC-3 stipulations for site effects conform with these assessments.

References

Erdik, M. (1979). A Single-Degree-of Freedom Model For Nonlinear Soil Amplification, USGS, Open-File Report 79-592.

Joyner, W.B. and A.T.F. Chen (1975). Calculation of Nonlinear Ground Response in Earthquakes, Bull. Seism. Soc. Am. 65, 1315-1336.

Martin, P.P. and H.B.Seed (1978). MASH, A Computer Program for the Non-Linear Analysis of Vertically Propagating Shear Waves in Horizontally Layered Deposits, U.C. Berkeley, EERC, Report No.78-23.

Hardin, B.O. and V.P.Drnevich (1972). Shear Modulus and Damping in Soils: Measurement and Parameter Effects, ASCE, Journal of Soil Mechanics and Foundations.

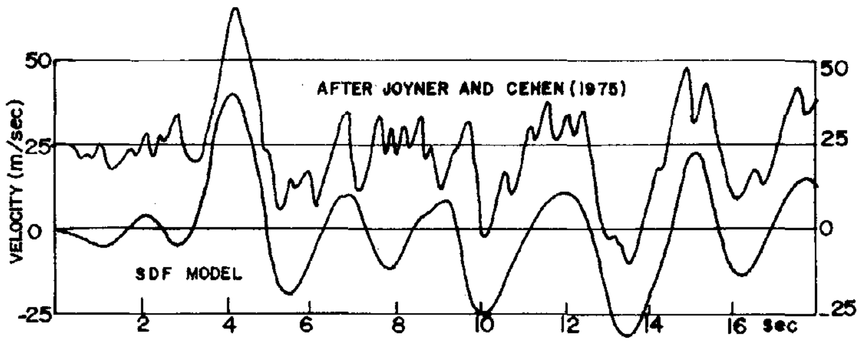


FIG. I FIRST TEST CASE

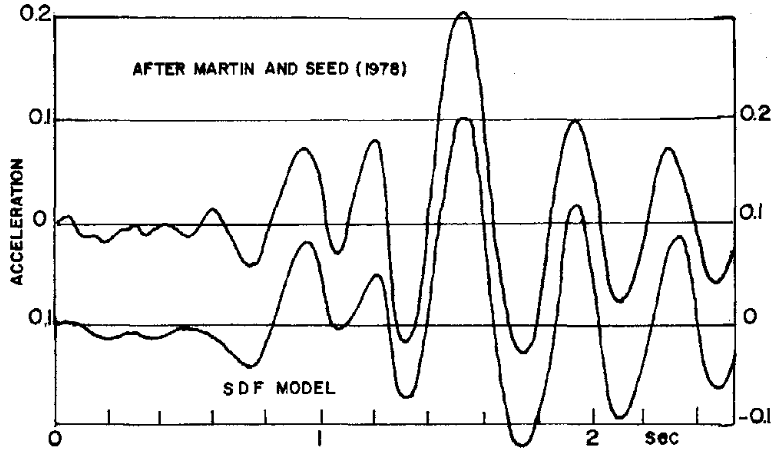


FIG. 2 SECOND TEST CASE

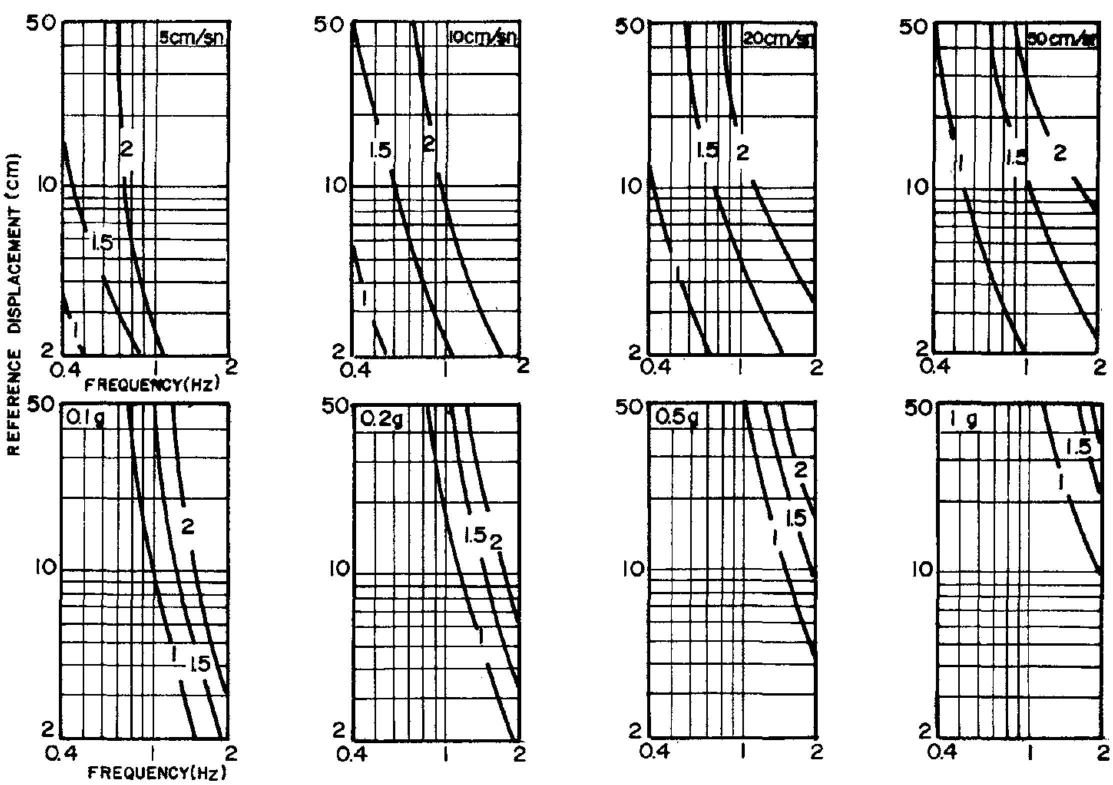


FIG. 3 ISO-AMPLIFICATION CONTOURS

KEIITI AKI

Massachusetts Institute of Technology

The objective of our project is to predict earthquake strong motions in a seismic area where little or no historic earthquake data exist. The need for such prediction is quite urgent, especially for siting critical facilities in relatively aseismic areas such as the eastern United States. Our approach to this outstanding unsolved problem is to predict strong motion on the basis of the laws of physics using information on the tectonic stress and physical properties of the earthquake fault which can be measured at the present time. Recent advances in the study of earthquake source mechanisms, plate tectonics, rock mechanics, and seismic wave propagation in realistic media have made this approach viable and promising.

An increasing number of seismologists at more than half a dozen universities and several research institutions are now working along this line of approach. A variety of earthquake modelling and computational procedures are being developed by various groups as presented in the NSF seminar-workshop on strong ground motions held in February, 1978.

A major break-through was made in our project on the computational procedure for simulating strong motion. Bouchon has succeeded in extending the discrete-wave-number representation method developed by Bouchon and Aki to three-space-dimensional cases. We can now calculate the seismic motion due to an earthquake fault rupture having an arbitrary space-time slip function embedded in an arbitrarily layered half-space.

We used the new method to study the interaction of a low-velocity surface layer and rupture propagation in the basement rock for both strike-slip and dip-slip earthquakes. We found a pronounced effect of low-velocity layers on the amplitude and duration of the ground shaking, as described later.

The new method was also used in simulating the long-period (longer than 5 seconds) seismic motion from the great 1857 earthquake of California, using the detailed distribution of slip recently published by Sieh. Snapshots of the spatial pattern of seismic motions throughout central and southern California as well as the time-domain seismograms were calculated at selected locations.

The new method was, then, used for reexamining the station No. 2 record of the Parkfield earthquake of 1966. The inclusion of the surface-layer effect made more realistic evaluation of the slip function than in previous attempts using a homogeneous full-space or half-space. The resultant slip function was, then, interpreted in terms of a barrier characterized by Griffith's surface-energy and Barenblatt's cohesive force. The physical model of barriers and geological observations on the great 1857 earthquake are then combined to offer a physical basis for the dependence of barrier interval on earthquake magnitude.

Another problem we are working on is the attenuation of shear waves in the lithosphere for the frequency range from 1 to 25 Hz. We found that the quality factor Q depends strongly on frequency, in the form of $Q = Q_0 f^m$, where m is from 0.5 to 0.8 depending on the area. The consequence of this work on our present project is grave and far-reaching, since the frequency range and wave propagation paths are directly relevant to Earthquake Engineering.

J. B. SAVY

Massachusetts Institute of Technology

Overview of the Project

The project addresses engineering strong ground motion estimation procedures based on combining empirical records and theoretical models. The latter are used, on one hand, to understand seismic energy propagation in the development of functional forms for such things as peak ground motion attenuation, and on the other hand, to study network-induced biases in actual recorded data.

At the present time our group is working on four specific problems as follows:

- Development of a ground motion model
- Estimation of parameters for the above model
- Preliminary study of network induced biases
- Study of seismic hazard attenuation laws.

Ground Motion Model

The approach is based on the idea that an earthquake fault is not a single smooth rupture over the entire fault plane, but consists of multiple patches breaking in a non-coherent manner. The acceleration at a given site is computed by superposition of the effects due to each patch, assuming a homogeneous and isotropic medium. The present model is an extension of the author's model (Savy, 1978) where the solution is improved for the intermediate to near field by addition of second-order distance terms, and by computing the three components of the P and S motion instead of only S. The input parameters are the seismic moment, the average coherence length of the rupture patches, the average rupture velocity, the (dislocation) rise time, and an empirical relationship between the seismic moment and the dimensions of the fault. Coherence length, rupture velocity and rise time are random variables varying from patch to patch with assumed probability distributions . A detailed parametric study is being performed which will define the limitations of the model uses and allow a better understanding of the (assumed) source behavior. The next improvement anticipated is the development of an analytical solution for the Power Spectral Density (PSD) of an ensemble of earthquakes occurring on a given fault thus allowing an analytical definition of the statistical characteristics of possible earthquakes at a given site.

Parameter Estimation

Based on the work of Aki (1979) and Sato & Hirasawa (1973) a model is developed which details the faulting process most responsible for the high frequency content in the near and intermediate field. The theoretical PSD (defined essentially by three parameters: Seismic moment, corner frequency and high frequency decay) is computed and compared with the PSD of the strong motion part of an actual record. By fitting the theoretical spectrum to the actual one the corner frequency and attenuation frequency dependence are determined. The corner frequency, in turn will give the average intervals between barriers of the source, thus enabling the estimation of the coherence length to be used in the ground motion model. The use of this technique, now under development, requires the establishment of a data file which includes all the source parameters needed in the computation of the theoretical spectrum. This requirement limits the number of actual records which can be analyzed.

Study of Network-Induced Biases

A preliminary study is underway which assumes a given "real" law of energy attenuation and simple fault and strong-motion network arrangements. An ensemble of acceleration values is generated by simulation for different instrument locations. From this synthetic data, "empirical" (different in functional form from the "real" law) attenuation laws are estimated by using ordinary or weighted least square techniques. As expected, the instrument network introduces a bias which can be quantified. Several techniques are being tested which, by weighting the data in some way, generate an ensemble of network-independent data points. Further studies will include realistic synthetic ground motion studies using the above ground motion model and actual instrument networks which will permit us to refine and test the technique for use with actual ground motion data.

Study of Seismic Hazard Attenuation Laws

A theoretical investigation was carried out in the area of seismic attenuation laws to ascertain the adequacy of current popular forms. The results of regression analysis showed that (1) linear attenuation forms satisfy the underlying assumptions of the statistical model, (2) acceleration is a function of site soil condition in conjunction with magnitude but not distance, and (3) linear functions poorly represent acceleration in the near field.

The results of robust regression analysis on the same strong motion data set (assuming a linear model) display only minor differences from the linear attenuation form, typically less than 0.05g over all magnitudes and distances. Therefore, the robust models also poorly represent accelerations in the near field. However, a linear model assuming normally distributed errors in magnitude and distance indicates a high degree of sensitivity in the prediction attenuation law over a reasonable range of variances for magnitude and distance.

Several non-linear attenuation models solved by the Marquardt iterative technique indicate that the sparsity of near field data results in predictive models that are highly sensitive in the near field to the forms assumed. Far field prediction with all non-linear attenuation laws is comparable with the popular linear model (Askins 1980).

Acknowledgments

This research, supported by NSF Grant PFR7827068, is under the supervision of Professor C. A. Cornell and with the participation of graduate students A. Papageorgiou, G. Toro and R. Askins.

References

Aki, K. (1979), Characterization of Barriers on an Earthquake, JGR, Vol. B11, p. 6140.

Askins, R. (1980), Advanced Statistical Techniques for Seismic Hazard Attenuation Law Estimation. MS Thesis, MIT.1980.

Sato & Hirasawa (1973), Body Wave Spectra from Propagating Cracks, J. Phys. Earth, 21, p. 415-431.

Savy, J. (1978), Determination of Seismic Design Parameters, a Stochastic Approach, The John A. Blume Earthquake Engineering Center, Stanford Report No. 34.

R. F. DRENICK

Polytechnic Institute of New York

The development of the critical excitation method has been reported on at several UCEER meetings. At about the time of the most recent one, the development was judged to have completed the basic research phase and to have reached the point at which its appeal to potential users should be explored. This summary recapitulates briefly the motivation for the method, sketches the method itself and then reports on the experience so far with the effort of gaining user acceptance.

The critical excitation method is for the assessment of the earthquake resistance of structures. The incentive for its development was the wish to have a method that would lead to assessments on as high a level of assurance as is compatible with current information regarding the nature of strong ground motion at a particular location. In order to achieve such a level, a method must avoid all information that is not available on a comparable level, but it must utilize all that is.

The critical excitation method, it is felt, does this. It fully exploits existing ground motion data regarding frequency content, time envelope and local overburden characteristics. On the other hand, it avoids most customary assumptions of a statistical nature which lead (demonstrably) to a degradation in the confidence level. In this way it arrives at assessments of earthquake resistance which are somewhat conservative, but whose conservatism may not be negotiable downward to any great extent, at the present state of knowledge regarding seismic events.

The National Science Foundation which had supported this line of research encouraged a search for potential users of the method among Federal Government mission agencies. In fact, it was actively helpful with it, being careful at the same time to avoid the impression of an endorsement of the method as such. Contact was established with five government offices. Two of these declined to pursue the matter even as far as a presentation. Two others permitted presentations but, for different reasons, declined to go beyond them.

A fifth agency (the Structural Engineering Research Branch of the Nuclear Regulatory Commission) expressed an interest. It pointed out that the critical excitation method, as then conceived, improperly avoided the use of two highly reliable pieces of information, namely, the limits on ground acceleration and velocity. After a modification to include them, the Commission authorized a large engineering firm to undertake the analysis by the method of two nuclear reactor structures and to report on its experience with it.

A preliminary version of this report has recently been completed. The conslusions the firm arrived at appear to be the following:

1. The critical excitation method is of potential utility in the seismic analysis of nuclear reactor structures.

2. The assessments of earthquake resistance arrived at by the method are comparable in conservatism with those obtained from methods currently in use, provided that similar assumptions are made regarding the desired structural resistance.

3. The utilization of the two additional pieces of information does not appear to have a strong bearing on the assessments (the implication thus being that they are essentially subsumed under the information that had formed the basis of the method previously).

NEIL W. POLHEMUS and AHMET S. CAKMAK

Princeton University

Parametric time series analysis of earthquake ground motion has the potential for characterizing observed series in terms of a small number of parameters. Such parsimonious representations are important for separating site-specific and quake-specific characteristics. However, application of stationary models requires a method for dealing with a time-dependent variance. Simulation from the fitted models can also produce multiple realizations with similar characteristics for input to structural experiments. Validation of the models depends in part on the similarity between the response spectra for the observed and simulated series.

Parametric Time Series Modeling

To describe acceleration as a discrete stochastic process, we postulate a model of the form

$$Z_t = \sum_{j=0}^{\infty} \psi_j g(t) a_{t-j}$$

where the ψ_j are constant coefficients, $\{a_t\}$ is a white noise process, and $g(t)$ induces a change of variance as a function of time. To fit a model to an observed series, the following procedure is used:

Step 1: Estimation of $g(t)$ through a polynomial model for $\{Z_t{}^2\}$ after an appropriate Box-Cox transformation [1].

Step 2: Stabilization of the acceleration variance using the untransformed variance polynomial.

Step 3: Estimation of a stationary ARMA model for the variance-stabilized acceleration series [2].

Simulation

Simulated acceleration time series are produced by generating realizations from the fitted ARMA models and scaling the data according to the estimated variance polynomial.

Figure 1a shows a typical horizontal acceleration component from the San Fernando Earthquake (M_L=6.3) recorded at 8244 Orion Blvd. (comp N00W, Caltech record no. C048). Figure 1b shows a simulated series following the above procedure. Figure 2a shows the fitted variance polynomial in the transformed metric, and Figure 2b the series after variance stabilization. Figure 2c shows the ARMA (2,1) simulation of the variance-stabilized series. It appears that this model consistently explains most of the time dependent structure of the variance-stabilized series, with little reduction in mean squared error for higher-order models [3].

To compare the observed and simulated data, response spectra are calculated. Figures 3a, b, c show typical acceleration, velocity and displacement spectra for the observed series (dots) and three simulations from the same model, in this case for 5% damping. Good agreement is achieved consistently except for periods in excess of approximately eight seconds, where preprocessing of the data has a significant impact.

Comparison of Series

When the process was repeated on the other two components of the selected earthquake record, very close agreement was observed among estimated ARMA (2,1) model parameters. This process will be repeated at a number of other selected sites for earthquakes of various magnitudes in order to determine whether the model parameters can be linked to site or quake-specific characteristics. Multivariate models to describe the three components simultaneously are also being fitted.

References

[1] G.E.P. Box and D.R. Cox, "An analysis of transformations," Journal of the Royal Statistical Society B 26, 211-252 (1964).

[2] G.E.P. Box and G.M. Jenkins, Time Series Analysis Forecasting and Control, Holden-Day, San Francisco (1970).

[3] N.W. Polhemus and A.S. Cakmak, "Simulation of Earthquake Ground Motion Using Parametric Time Series Models," Dept. of Civil Engineering technical report #80-SM-2, Princeton University, Princeton, N.J.

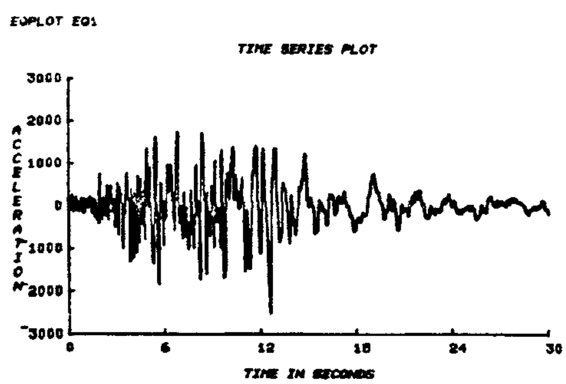


Figure 1a - Observed Acceleration

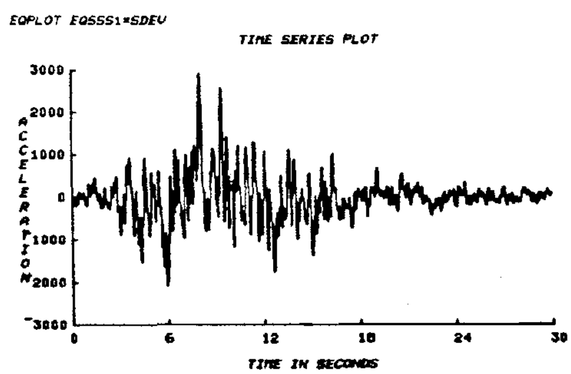


Figure 1b - Simulated Acceleration

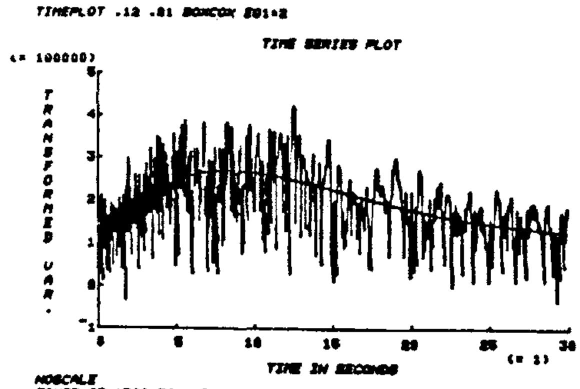


Figure 2a - Variance Polynomial under Transformation

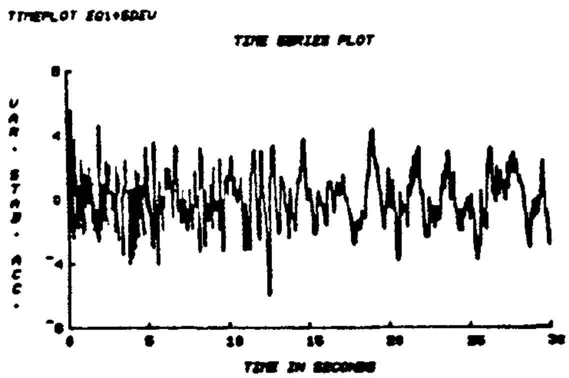


Figure 2b - Variance Stabilized Acceleration

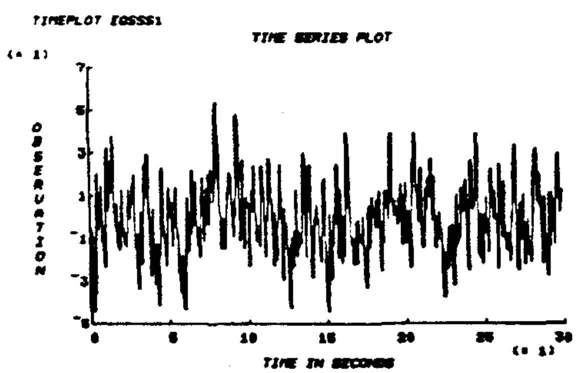


Figure 2c - Simulated Series from ARMA Model

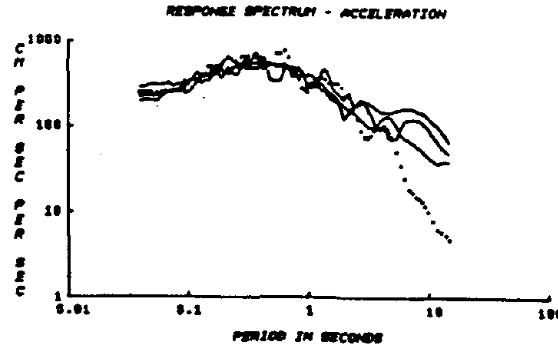


Figure 3a - Acceleration Response Spectra-5% Damping

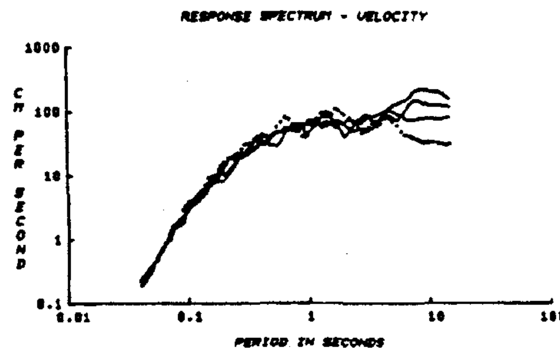


Figure 3b - Velocity Response Spectra-5% Damping

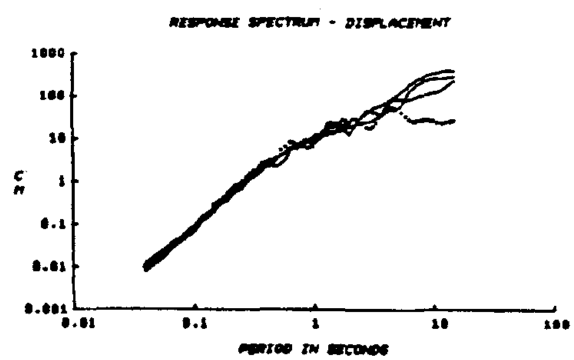


Figure 3c - Displacement Response Spectra-5% Damping

THEODORE C. ZSUTTY
HARESH C. SHAH

Stanford University

This paper summarizes research currently sponsored by the National Science Foundation on the Description of Seismic Ground Shaking for Structural Design Applications.

Description of Results and Applications

The large sample histogram or frequency distribution of the family of absolute peak values of robust earthquake accelerograms has been found to be well modeled by the exponential probability distribution function. Further, using the theory of extremes, the mean and variance statistics of the largest peak acceleration (PGA) are predicted in terms of a standardized sample size N^* of the number of peaks. The exponential model and extreme value theory also apply to acceleration response peaks in the spectral period range of 0.1 to 1.0 seconds. This research proposes to employ this statistical knowledge concerning the mean or expected values of PGA and spectral ordinates S_a to improve upon the description of load criteria in existing and tentative seismic design recommendations. Specifically the zone factor Z is the Uniform Building Code and the A factors in the tentative ATC-3 provisions have been evaluated with either subjective estimates or highly variable acceleration attenuation information. Similarly, the spectral shape representations (CS) in the code and its counterpart in ATC-3 are based on statistical averages of spectra which have been normalized by the single observed (not mean value) PGA of each spectral record. A high degree of spectral ordinate variance has been created by this means of spectral normalization and by the use of many non-compatible records having both near (10 km) and far (100 km) epicentral distances.

The main research objectives will be to employ the exponential and extreme value behavior of robust earthquake acceleration peaks to: formulate improved attenuation prediction for the spectral scaling factor "A"; and to better define spectral shapes (DAF) for given site and source conditions. Related research objectives will concern the refinement of the statistical analysis of acceleration peaks, and studies concerned with why the exponential model generally typifies the strong long duration character of the favorite engineering time histories such as El Centro 1940, and Taft 1952.

S. F. BORG

Stevens Institute of Technology

A model -an equation- a "mechanism" is obtained for a deep-focus earthquake, i.e., one which is generated in the mantle, say between 50-800 km below the surface of the earth. The model is based upon the conservation equations of mechanics appropriate for the phenomena use in conjunction with a number of physically reasonable considerations. These equations are transformed by utilizing a fundamental similarity coordinate and the resulting field equations and boundary conditions are solved in a closed form. The analysis permits a consideration of energy computations. This research is sponsored by the National Science Foundation.

The Mathematical-Physical Model

Deep within the mantle, where the earthquake is assumed to occur we have a condition of hydrostatic stress. This is a zero, initial condition. Due to tectonic plate movement of the crust of the earth (or other causes), a tensile stress σ_o is added to a strip of mantle of thickness, t. This stress is assumed uniform along the edge of an enclosed area of indefinite extent and we consider the affect of σ_o alone. These (very high) stresses σ_o introduce a strain energy in the layer caused by stretching. The stress σ_o gradually increases and builds up as the tectonic plate action proceeds. Finally, a value of σ_o is reached which in conjunction with the initial state of the layer and a possible phase change leads to a "rupture" or "fracture" initiated at a single point A. (It is interesting to note that Benioff has suggested on the basis of observed wave forms from three earthquakes that a class of deep earthquakes may arise when a phase transition occurs thorugh a region of rock, causing a sudden change in volume). This failure at A spreads circularly throughout the layer, with the outer reach of its effect travelling with the velocity of small disturbances and the velocity of formation of the ruptured area as determined by the field equations.

Mathematical Analysis

For the dynamic phenomenon being investigated in this paper, the material may be assumed to have the properties of a border region fluid-solid. Therefore the analysis may be based upon the conservation equations of continuum fluid mechanics instead of the somewhat uncertain relations of combined dynamic elasticity-plasticity action, as is usually done in analyzing fracture phenomena.

Utilizing these equations and a similarity transformation appropriate to the phenomena, one obtains finally a value for the "critical" stress, σ_o, which initiates the rupture-the earthquake. This is given by

$$\sigma_o = \frac{0.92\rho_o C^2 + \sigma_{\Theta F}}{2(1+\nu)} \qquad (1)$$

in which

ρ_o = initial density of the layer

C = velocity of sound of small disturbances in the stressed strip and determines the outer-reach-of-effect.

$\sigma_{\Theta F}$ = fracture stress of the layer

ν = Poisson's ratio of the layer

Then using this solution in conjunction with an elastic strain energy analysis, it is possible to relate the mechanism to earthquake energy. A typical computation indicates reasonable values.

Under Study and Still to be Done

Extensions of the theory are currently being studied and data is being sought to check the various predictions of the new mechanism. Among the topics being investigated are:

1) Values of the physical constants that occur should be determined. These will have to come from some of the centers working in deep-earth research, such as the one, for example, at Cornell University.

2) Is there any evidence -geologic, seismograph, accelerogram, observation- that tends to confirm or contradict the proposed model, for deep focus earthquakes?

3) Among the behaviors to look for are

   a) A "pulsating" loading with the corresponding P and S waves.

   b) An enormous release of energy in a matter of seconds.

   c) Energy release from a layer or area a mile (miles) in extent - or a thicker strip of lesser area.

   d) Surface movement which leads to the build-up of the stress σ_o.

   e) A phase change of the material which, in conjunction with σ_o results in a triggering instability-fracture or rupture.

   f) A "healing" of e) due to the high pressures involved.

   g) Any clues in the proposed mechanism that would lead to a prediction of a possible earthquake.

h) Any means for triggering or defusing an earthquake due to the suggested mechanism.

4) Finally, can the proposed mechanism be connected with the Richter scale?

The complete analysis is contained in "A Mathematical Physical Model of a Deep-Focus Earthquake Mechanism", Technical Report ME/CE-79, November 1979, Stevens Institute of Technology.

S. F. BORG

Stevens Institute of Technology

This research presents a new unifying concept or invariant for the accelerogram, one of the basic records of an earthquake. The model is based upon a rigorous mathematical and physical argument and has been checked against different earthquakes in various parts of the earth. In addition a new damage criterion based upon the parameters of the invariant will be described.

The Accelerogram Invariant

In developing the accelerogram invariant, an envelope is formed of the positive portion of the accelerogram between the time t=o (the initiation of the earthquake record) and $t=t_f$, the end of the earthquake record. It is assumed that t_f and $\Sigma(a\Delta t)$ are the fundamental parameters of this record. $\Sigma(a\Delta t)$ is the area under the envelope between t=o and any time t=t. Then, proceeding as in Borg, 1974, we obtain finally, the relation

$$\frac{\Sigma(a\Delta t)}{\Sigma(a\Delta t)_f} = e^{K\left[1-\left(\frac{t_f}{t}\right)^n\right]} \qquad (1)$$

in which K and n are constants to be determined from a study of actual accelerograms. Accelerograms from the Tolmezzo (1976), Taft (1952), Lima (1966), San Fernando (1971) and Bucharest (1977) earthquakes were analyzed and the single equation -the invariant- which applies to all is

$$\frac{\Sigma(a\Delta t)}{\Sigma(a\Delta t)_f} = e^{0.12\left[1-\left(\frac{t_f}{t}\right)^{1.8}\right]} \qquad (2)$$

The fundamental -the global- parameters for these earthquakes are as follows:

Earthquake	t_f, seconds	$\Sigma(a\Delta t)_f$, "g" seconds
Tolmezzo	20	0.98
Taft	20	0.96
Lima	20	1.84
San Fernando	48	1.06
Bucharest	14	0.72

TABLE 1

In a tentative uniqueness-existence hypothesis developed in connection with Eq. 1, K and n are ultimately related to

1) the soil or geological conditions at the point where the accelerogram is obtained. This influences t_f
2) $(a\Delta t)_f$ is the parameter influenced by total surface horizontal energy per unit ground area at the site where the accelerogram is obtained.

This implies that t_f and $\Sigma(a\Delta t)_f$ vary depending on the above factors. Further studies are in progress to clarify and check this hypothesis.

A related, though different analysis leads to a parallel equation to Eq. 1. This leads to an expression for the surface horizontal energy per unit time supplied by the earthquake at the site where the accelerogram is recorded. For the K and n values given, we find that this quantity varies inversely as the $t^{2.8}$ -a prediction which should be capable of checking.

Note- if the accelerogram is too complicated to be represented by the simple Eq. 1, then it is conceivable that the record is due to a series of closely spaced shocks and a superposition of several Eq. 1, with time lags may represent the event. This -if verified- would introduce an entirely new procedure for studying the strengths and properties of earthquakes. Studies are also being pursued in this direction.

The Damage Contour Map

t_f and $(a\Delta t)_f$ are assumed to be the fundamental parameters of the accelerogram invariant. Furthermore, on physical grounds it seems reasonable to assume that the damage inflicted in a structure at a given location is related to the acceleration of the ground at that location.

Based upon the foregoing and utilizing available records concerning damage (or intensity) at the locations of the accelerograms considered, a "Damage Contour Chart" may be constructed, with t_f and $\Sigma(a\Delta t)_f$ as the coordinates and curves separating regions of approximately equal intensity.

Studies are underway in an attempt to alter the chart to account, in some simple reasonable fashion, for the variatin of frequencies, since these probably have an influence on the damage.

Acknowledgement

This research was supported by a National Science Foundation Grant No. PFR 7822846. The more complete, detailed study is contained in Borg, 1979.

Reference

S.F.Borg - Similarity Solutions in the Engineering, Physical-Chemical, Biological-Medical and Social Sciences, Proceedings of Symposium "Symmetry, Similarity and Group Theoretic Methods in Mechanics", Ed. P.G. Glockner and M.E. Singh, Univ. of Calgary, Aug. 1974, pp. 263-282.

S.F.Borg - Accelerogram, Intensity, Damage- A new Correlation for use in Earthquake Engineering Design, Technical Report ME/CE-791, December, 1979, Stevens Institute of Technology.

STRUCTURAL ELEMENTS

N.D. NATHAN
D.L. ANDERSON
S. CHERRY

University of British Columbia

The rational design of reinforced concrete masonry walls for seismic forces is presently being studied. This includes the preparation of dynamic amplification spectra for the seismic response at different levels within a masonry building and the initiation of a test program intended to furnish some of the design parameters.

Introduction

The purpose of the present investigation is to examine the adequacy of the National Building Code (Canada) limitations on amounts and spacing of masonry wall reinforcement, which it is believed are based on the observation of successful past practice and which have a considerable economic impact on the use of masonry walls. The efficiency of joint reinforcement in this context is also under consideration. Attention is being directed initially to the out-of-plane forces acting on such walls. Future studies will include the response to in-plane forces as well.

The results of initial analytical studies of seismic force intensity expected at different levels in typical masonry buildings as a result of different earthquake strengths are reported and an expression is offered for estimating the fundamental period of masonry high rise buildings. The preliminary results of monotonic quasi-static lateral load tests on reinforced wall panels are also discussed. Quasi-static cyclic tests and dynamic tests on a shake table facility will be included in the total program.

Magnitude of Out-of-Plane Forces

The seismic forces induced at any floor level can be defined in terms of a height dynamic amplification factor as a function of building period. An elastic modal analysis using the response spectrum approach has been performed on reinforced masonry shear and infill wall systems to determine the dynamic amplification factors at various height levels. Fourteen buildings in three plan forms ranging in height from five to twenty five storeys were modelled in this study.

The dynamic amplification at various levels throughout the building were plotted against fundamental period, and upper bound curves were drawn. Fig. 1 shows the family of curves for five levels. These curves permit computation of the maximum seismic force at any point in the building given the peak ground acceleration and the building period. For the buildings studied, it was found that the fundamental building period, T_m (secs), could be approximated by

$$T_m = (0.35 \pm 0.5T)T$$

where $T = 0.05\ H/\sqrt{D}$; H = building height (ft) and D = plan dimension in direction of motion (ft).

Lateral Load Tests

Tests are in progress to determine the parameters governing the spacing of principal reinforcement and the design of distribution steel. The efficiency of joint reinforcement in either role is also being studied. To date fourteen walls have been tested, 8 spanning vertically and 6 horizontally. The test specimens, with minor exceptions, have all been 8 x 8 ft. panels built of 8 x 8 x 16 in. ungrouted hollow concrete blocks in running bond construction. Reinforcement was grade 60 reinforcing bars in grouted cores or bond beams, and 9 gauge ladder type joint reinforcement. The walls with vertical main steel all had 2-#6 bars for a steel ratio of 0.0011; #4 and #6 bars in bond beams, or joint reinforcement, was used in walls with horizontal main steel. The walls were tested in the vertical position and loaded by means of an air bag placed between the test panel and a reaction wall. Measurements were taken of lateral displacements and pressure and of reinforcing bar strain.

Test Results

Results from initial tests with main steel at 48 ins. spacing (NBC maximum limitation) showed that failure did not occur in the blocks between the main reinforcement. The spacing was then increased in stages to 72 ins. The masonry was able to span at least 56 ins. between main steel at high load, but in tests with a steel spacing of 72 ins. the walls failed by a bending mechanism between main reinforcement, although a high load was still obtained. Typical results are shown in Fig. 2.

Distribution steel in the form of joint reinforcement or bond beams was then added to determine the effect on the failure mechanism, with main reinforcement at 72 ins. The joint reinforcement was placed in every course so as to give the same reinforcement ratio as #4 bars at 48 ins. spacing; this was the actual steel size used in the bond beams. The wall with joint steel failed by a bending mechanism in the blocks, while the one with bond beams failed in bond on the horizontal #4 bar. Primary bending capacity was fully developed in both cases. The wall with the joint distribution steel performed better in the sense that there was less sign of distress before failure. Typical results are shown in Fig. 3.

To date the horizontally spanning walls have included main steel spacing of 48 ins. and 72 ins. and walls with only joint reinforcement as main steel. No vertical distribution steel has yet been used in this series of tests. For all these walls the failure load was nearly the same: 125-130 psf., although failure modes appeared to be in either transverse or primary bending. There was no cracking and little deformation up to the failure load, after which the load capacity dropped off with increased deflections. Typical results are shown in Fig. 4.

Final Remarks

It is expected that the results obtained from an extended program of the described tests will form a basis for designing the economical spacing of the main steel and the appropriate amount and spacing of distribution steel to carry the out-of-plane seismic forces acting on masonry walls. These forces can be quickly computed for the relevant level of ground motion through the concept of storey height dynamic amplification factors.

Present indications suggest that for typical storey heights main steel may be spaced at more than 4 ft. and still develop the full primary bending moment. Joint reinforcement appears to be effective as distribution steel for vertical spans or as main steel for horizontal spans. It is emphasized that these results are only tentative and must be treated with considerable caution at this stage since they are based only on quasi-static monotonic load tests. Future studies being planned will include dynamic loading effects.

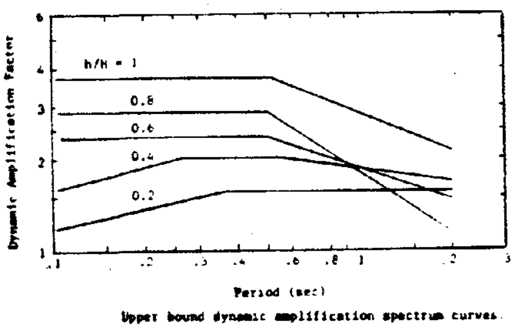


Figure 1

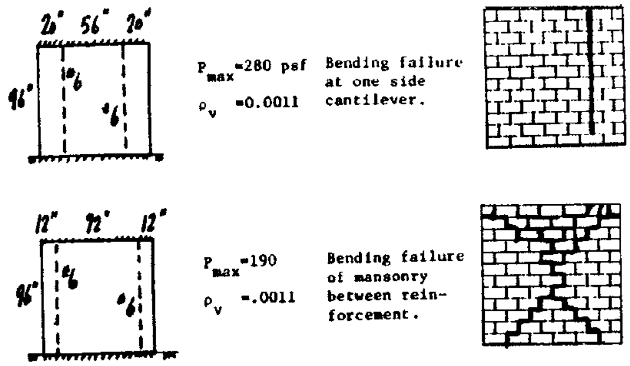


Figure 2

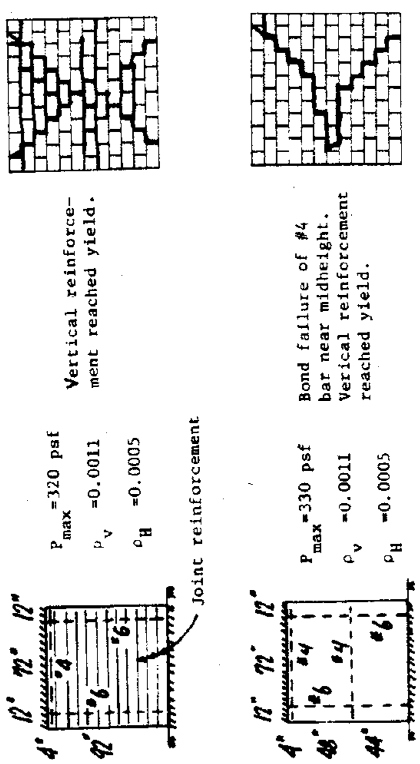


Figure 3

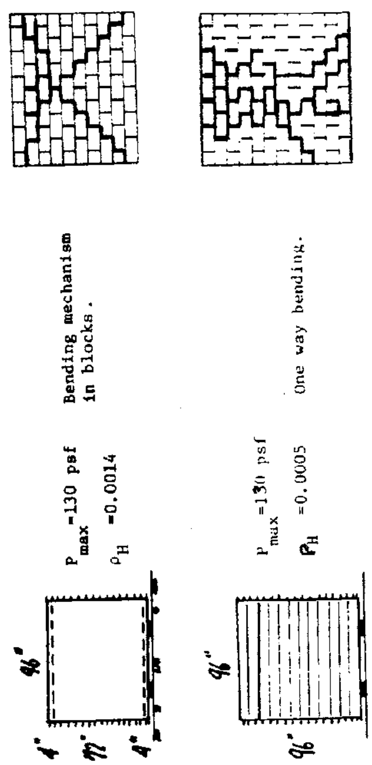


Figure 4

PETER GERGELY
RICHARD N. WHITE
ANTHONY R. INGRAFFEA

Cornell University

Several current research projects in the Department of Structural Engineering at Cornell University concerned with the seismic behavior of reinforced concrete structures are described in this paper. The projects include the study of in-plane cyclic shear and the punching shear transfer in biaxially tensioned and cracked concrete slabs or walls, the design of lapped splices for inelastic cyclic loading, and reversed cyclic force transfer between deformed bars and concrete.

In-Plane Cyclic Shear in Biaxially Tensioned Slabs

The strength and stiffness of concrete wall elements subjected to preset biaxial tension and cyclic membrane shear are studied experimentally. Over forty experiments on 6-in. thick, 4 ft square elements have been completed. The main variables include the level of biaxial tension, the load history, the percentage of orthogonal reinforcement, the presence of additional diagonal steel, and the sequence of application of tension and shear. Preliminary results have been reported in several publications [1,2,3]. Current work includes experiments in which tension is applied in only one direction and specimens with construction joints.

The experimental results reveal a highly nonlinear hysteretic shear-slip behavior consisting of very low stiffness at low shear stresses and high stiffness at shear stresses above about 50 psi. Diagonal cracks generally initiate at relatively low shear stresses (on the order of 100 psi) but this may be due to the additional effects of shrinkage stresses. All specimens have failed in diagonal tension from yielding of the reinforcement rather than by sliding shear.

The results are applicable to the design and analysis of wall type structures where tension exists prior to or during the application of seismic shear; for example, in pressurized reinforced concrete nuclear containment shells or in off-shore concrete towers.

This project is sponsored by the Nuclear Regulatory Commission.

Punching Shear and Biaxial Tension

Specimens similar to those described above are subjected to punching shear (also called peripheral shear). In the first series of tests the bars in two layers of orthogonal reinforcement were spaced 6 inches apart in both directions. The reinforcement was tensioned to various levels; to about $0.6F_y$ in most experiments. The punching load was applied through 4 inch square steel pads positioned between four cracks that generally occurred along the reinforcement. The reaction below the slab was 6 inches from the edges of the loading pad.

A complete punchout failure occurred in all tests, accompanied by considerable cracking visible on the bottom face. Often spalling and horizontal splitting (layering) also developed.

Results obtained so far indicate [4] that the punching shear strength is only slightly influenced by the level of biaxial tension. The shear strength ranged from about 520 psi for zero biaxial tension (but precracked specimens) to about 400 psi for 0.9f tension in the reinforcement. These stresses are calculated for a perimeter equal to four times the slab thickness of 6 in., which corresponds to a perimeter located 0.22d from the loading pad.

Both the variation of punching strength with tension and the magnitude of shear stress are significantly different from the expressions used by ACI Committees 349 and 359.

The investigation is continuing using specimens with varying reinforcement ratios, spacing of steel, size of load pad, and different shear spans. This research is sponsored by the Nuclear Regulatory Commission.

Lapped Splices in Beams

The strength and ductility of beams with lapped splices has been studied with about 40 full-scale and 8 half-scale beams [5]. The principal variables were the load history and the amount and distribution of transverse reinforcement.

The primary aim of the investigation is to study whether it is possible to design lapped splices in inelastic regions of frames. Therefore, most beams were subjected to various load histories beyond yield; in some cases the load was reversed.

The results show that it is possible to design lapped splices to sustain a few dozen cycles of repeated loading beyond yield, typically up to about twice the yield deflection, if closely spaced stirrups are used over the entire length of the splice which is at least 30 bar diameters in length. In these beams twice the beam yield deflection corresponded to about three times the yield strain in the spliced bars made of 60 ksi steel.

If stirrups are provided throughout the splice, damage penetrates slowly from both ends of the splice, until the effective length of the splice is reduced. Damage continues to spread if the level of cyclic load is above about 80% of yield.

The amount of stirrups required for satisfactory performance for repeated inelastic loading is about twice the amount recommended for static loading by ACI Committee 408 [6]. Furthermore, the spacing and distribution of stirrups is also important.

Most of the splices were located in the constant moment region of beams loaded with two third-point forces. A few splices were in the shear zone and they behaved better than those in the constant moment region because the moments at the two ends of the splice were unequal.

Other variables currently being investigated include various levels of load reversals, the cover over the splice, and splices in columns. This study is sponsored by the National Science Foundation.

Steel-Concrete Interaction

The force transfer mechanism between deformed steel bars and concrete is highly nonlinear. The major causes of nonlinear behavior are local cracking at bar ribs and crushing of concrete in front of the ribs.

Both types of effects are investigated experimentally and analytically. Pullout tests are performed using bars with single or multiple lugs to evaluate the stiffness and cracking for cycling loading. As expected, the load-slip response is hysteretic and the curve consists of a portion with very low stiffness (almost free slip), followed by a region of high stiffness when the lugs press against crushed concrete. Cracking is studied with the help of ink injection.

The experimental work is accompanied by an analytical study of the force transfer. The finite element program under development traces the progress of cracking using fracture mechanics concepts. The stiffness characteristics of crushed concrete are obtained from the experiments.

The goal of this investigation is to develop an analytical model for the finite-element analysis of inelastic cyclic force transfer between steel and concrete. It is sponsored by the National Science Foundation.

REFERENCES

1. White, R.N., Perdikaris, P.C., and Gergely, P., "Strength and Stiffness of Reinforced Concrete Containments Subjected to Seismic Loading: Research Results and Needs," Proc. of Panel Session JK-P, 5th SMIRT Conference, Berlin, August 1979, pp. 77-113.
2. Gergely, P., and White, R.N., "Seismic Effects in Secondary Containments: Research Needs," Nuclear Engineering and Design, Vol. 50, 1978, pp. 41-47.
3. Gergely, P., and Smith, J.K., "Seismic Response of Cracked Cylindrical Concrete Structures," Proc. 2nd U.S. National Conference on Earthquake Engineering, Stanford University, August 1979, pp. 185-192.
4. Abrams, J.H., "The Punching Shearing Strength of Precracked Reinforced Concrete in Biaxial Tension - Phase I Results," M.S. Thesis, Department of Structural Engineering, Cornell University, May 1979.
5. Fagundo, E.F., Gergely, P., and White, R.N., "The Behavior of Lapped Splices in Reinforced Concrete Beams Subjected to Repeated Loads," Report 79-7, Department of Structural Engineering, Cornell University, December 1979.
6. ACI Committee 408, "Suggested Development, Splice, and Standard Hook Provisions for Deformed Bars in Tension," Proc. Concrete International, Vol. 1, No. 7, July 1979, pp. 44-46.

SUBHASH C. GOEL

The University of Michigan

This paper summarizes a current research program concerning the hysteresis behavior of bracing members and earthquake resistant design of braced frame structures of steel. Principal investigators are Professors Glen V. Berg, Robert D. Hanson and Subhash C. Goel. The research project is jointly sponsored by the National Science Foundation and the American Iron and Steel Institute.

BRACING MEMBERS AND BRACED FRAMES

Objectives

The main objectives of this research are:

1. To study the hysteresis behavior of steel bracing members and connections by theoretical and experimental means.
2. To formulate suitable hysteresis models for such members to be used in computing the inelastic dynamic response of braced structures.
3. To formulate design recommendations for improved seismic resistance of braced frame structures.

Previous Research

The study of hysteresis behavior of axially loaded steel bracing members and earthquake response of braced frames has been in progress at the University of Michigan since 1967. Earlier analytical work on axially loaded members by Higginbotham, Prathuangsit and Singh (1,2,3) and experiments on small size bar specimens by Kahn and Hanson (4) led to the conclusion that effective slenderness ratio is the single most important parameter affecting the hysteresis behavior of these members. This concept was further verified by Jain (5) by using small scale tube and angle specimens whith welded gusset plates at the ends and cyclically loaded in the axial direction. Jain and Goel (6) used the results of these tests in order to formulate an empirical hysteresis model which considers the reduction in compressive strength and increase in member length with number of cycles. This hysteresis model is called the Buckling Element.

It has been found that bracing members of intermediate to small slenderness ratios may develop significant end moments which should be considered along with buckling due to axial forces. As a first attempt to model this combined behavior in a simple manner Jain and Goel (6) developed their End Moment-Buckling Element for use with DRAIN-2D computer program for a practical inelastic dynamic analysis of braced frames. This element consists of two components, the buckling component and an end moment-axial force interaction component. The axial force in the members is governed by the buckling component which is then used to compute the plastic moment capacity and the plastic hinge formation at the ends. In this formulation the flexural stiffness of the member is assumed to be unaffected by the axial force. This model has permitted the study of effect of column buckling on the response of a seven-story concentric K braced frame subjected to a severe horizontal earthquake ground motion (7).

Jain and Goel (7) used their End Moment-Buckling Element to study the earthquake response of a seven-story structure with concentric K and split K bracing patterns with different member proportions. The frames were designed by allowable stress design procedures in order to obtain weak girder-strong brace, weak girder-intermediate brace and strong girder-weak brace proportions. These frames were subjected to two different horizontal accelerograms representing severe earthquakes. The results showed that the behavior and plastic hinge formation were quite different in the concentric K and eccentric split K braced frames. The response of these frames was also strongly influenced by the relative member proportions. It was noticed that strong bracing members generally caused excessive inelastic activity in the columns of concentric braced frames and in the girders of eccentric braced frames. Eccentric braced frames with slender bracing members are perferred since they seem to show the ductile behavior of open-moment resisting frames combined with the stiffness efficiency of braced systems.

Current Research

In the current phase of research (8) the hysteresis behavior of full size members is being studied through large scale tests on members in a realistic inclined geometry. The primary objective is to correlate the results with those on axially loaded small scale specimens in previous studies and to determine as to what extent the effective length concept is applicable to members loaded in the inclined geometry. Furthermore, cyclic load tests on full-size members allow a more realistic investigation of the behavior and influence of connection details than was possible with small scale specimens in previous studies. In the experimental set-up full-size members (length 3 m) are mounted diagonally in a four hinge frame and subjected to cyclic displacements. W-shapes and rectangular tubes are used as cross sections with welded connections, with and without gusset plates. The overall characteristics of the hysteresis behavior of these members appear to be quite similar to those of axially loaded small scale members. However, the fatigue life and failure pattern seem to be quite strongly influenced by local buckling and connection details. A finite element model is used for the analytical investigation of these members. The elastic effects are simulated with beam-column elements whereas the plastic deformations are concentrated in plastic hinges at the node points. The plasticity condition in its most general form incorporates the Bauschinger effect as well as strain-hardening. The variation of different assumptions with regard to geometric effects and the material behavior is being used in the interpretation of the test results and in identifying the physical reasons for the characteristics of the hysteresis loops.

Further Research

Whereas the current investigation of hysteresis behavior of full-size members will help to put the theoretical models on a more firm basis, further testing is planned to include angle and channel shapes with bolted/

welded connections and gusset plates. The emphasis in this phase will be on the influence and behavior of connection details. It is hoped that the results will lead to practical design recommendations regarding selection of proper proportions of the cross section and connection details of bracing members. At the same time the study of earthquake response of braced frames is being extended to formulate design procedures both at the working as well as ultimate strength levels for proportioning these structures to ensure their improved performance during moderate and severe earthquake ground motions.

REFERENCES

1. Higginbotham, A.B., "The Inelastic Cyclic Behavior of Axially Loaded Steel Members," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, January 1973.

2. Singh, P., "Seismic Behavior of Braces and Braced Steel Frames," Ph.D Thesis, The University of Michigan, Ann Arbor, Michigan, July 1977.

3. Prathuangsit, D., "Inelastic Hysteresis Behavior of Axially Loaded Steel Members with Rotational End Restraints," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, April 1976.

4. Kahn, L.F., and Hanson, R.D., "Inelastic Cycles of Axially Loaded Steel Members," Journal of the Structural Division, ASCE, Vol. 102, No. ST5, May 1976, pp. 947-959.

5. Jain, A.K., "Hysteresis Behavior of Bracing Members and Seismic Response of Braced Frames With Different Proportions," Ph.D. Thesis, The University of Michigan, Ann Arbor, Michigan, July 1978.

6. Jain, A.K., and Goel, S.C., "Hysteresis Models for Steel Members Subjected to Cyclic Buckling or Cyclic End Moments and Buckling," Report No. UMEE 78R6, Civil Engineering Department, University of Michigan, Ann Arbor, Michigan, December 1978.

7. Jain, A.K., and Goel, S.C., "Seismic Response of Eccentric and Concentric Braced Steel Frames with Different Proportions," Report No. UMEE 79R1, Univeristy of Michigan, Ann Arbor, Michigan, July 1979.

8. Gugerli, H., and Goel, S.C., "Large Scale Tests for the Hysteresis Behavior of Inclined Bracing Members," Proceedings, Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, September 1980.

WADI S. RUMMAN

University of Michigan

This research deals with the monotonic and cyclic behavior of reinforced concrete members of hollow circular section when subjected to bending with the presence of an axial load. Such members are encountered in many structures such as reinforced concrete chimneys, hollow circular bridge piers, offshore platforms and circular towers.

The most recent research on this topic at the University of Michigan has been experimental (1). Four specimens were tested monotonically and four other identical specimens were tested under reversed cyclic bending. All specimens were subjected to an axial load that remained constant during any one test. All specimens were 128 inches long and 16 inches in outside diameter and with a wall thickness of 2 inches. Specimens differed from one another in the value of the axial load and the amount of the longitudinal steel. The two most important parameters that influence the behavior could be expressed as the longitudinal steel parameter $\rho\ f_y/f_c'$ and the axial load parameter w/rtf_c', where ρ is the steel ratio, f_y is the yield stress of the steel, f_c' is the strength of the concrete, w is the axial load, r is the mean radius of the cross-section and t is the wall thickness. The effects of these parameters on the strength, stiffness, cracking pattern, failure mechanism, curvature ductility and energy absorption were studied.

The limited experimental research was compared to the theoretical investigations that were made previously at the University of Michigan (2). The theoretical predictions were based on Hognestad's (3) stress-strain relationship for concrete and on an elasto-plastic stress-strain curve for the steel.

The four monotonic tests have shown that the ultimate bending moments as determined from the tests were consistently higher than those predicted from theory (15%-40%). The difference between theory and test was more pronounced in specimens with low steel ratios and low axial load. If the steel hardening is considered in the conputations, then the above percentage differences will be reduced to about 10%-28%.

The limited cyclic tests have shown that the shape of the moment-curvature diagrams is affected primarily by the axial load parameter. Shapes similar to a parallelogram were obtained when the axial load was small (e.g., $w/rtf_c' \sim .1$) as compared to spindle-type diagrams exhibited with the higher (e.g., $w/rtf_c' \sim .3$) axial loads. For sections with small axial loads an idealized model such as Clough's (4) can be satisfactorily used. However, for sections with high axial loads, the existing idealized models need to be modified, as, for example, the modification suggested by Mokrin (1).

Future research in this area will include testing more specimens to incorporate additional variations in the longitudinal steel and axial load parameters. More theoretical work will be required with the goal of predicting more accurately the ultimate moment capacity obtained from tests. Future experiments will concentrate on specimens with thinner walls to represent more closely the r/t ratios encountered in many real structures. Tests will be needed to study the effect of shear on the ultimate strength and cyclic behavior of the specimens. Because some of the structures include openings, tests will be necessary to study the monotonic and cyclic behavior of the hollow circular reinforced concrete sections with openings.

References

1. Mokrin, Zamil A., "Reinforced Concrete Members of Hollow Circular Section Under Monotonic and Cyclic Bending," Ph.D. Thesis, Department of Civil Engineering, University of Michigan, Ann Arbor, December, 1978.

2. Sun, Ru-Tsung, "Inelastic Behavior of Reinforced Concrete Chimneys," Ph.D. Thesis, Department of Civil Engineering, University of Michigan, Ann Arbor, January, 1974.

3. Hognestad, E., "A Study of Combined Bending and Axial Load in Reinforced Concrete Members," University of Illinois Engineering Experimental Station Bulletin No. 399, 1951, p. 128.

4. Clough, R., and Johnston, S., "Effect of Stiffness Degradation on Earthquake Ductility Requirements," Proceedings of Japan Earthquake Engineering Symposium, 1966, Tokyo, Japan, pp. 227-232.

JAMES K. WIGHT

The University of Michigan

Reinforced Concrete Beam to Column Connections

This report summarizes a current experimental investigation of the behavior of reinforced concrete beam to column subassemblages subjected to a series of large load reversals. This investigation is a continuation of previous research (1,2) at the University of Michigan on the behavior of reinforced concrete members under seismic loading. The current and previous research projects have been sponsored primarily by the National Science Foundation.

Purpose and Background. The primary purpose of this investigation is to obtain experimental evidence which will justify a simplification of the existing seismic design recommendations (3) for the shear strength of reinforced concrete beam to column connections. The existing recommendations for connections have shear design provisions which are similar to those for beams and columns. However, experimental research projects at the Universities of Texas (4) and Michigan (1) have shown that the existing shear provision are not correct and may be too conservative in some instances. The results from Texas indicated a minimum amount of transverse reinforcement was required to develop and maintain a substantial shear strength under large load reversals. However, increases in the amount of transverse reinforcement above a certain level did not lead to better behavior. The results from Michigan emphasized the importance of the flexural strength ratio of the columns to the beams at a connection.

Experimental Program. Twenty four internal and external beam to column connections will be constructed and subjected to a laboratory loading routine intended to represent earthquake type loading. In order to more closely simulate real beam to column subassemblages, half of the specimens will have a floor slab and transverse beams in addition to the main beam and column. The other half of the specimens will be "bare" connections and are intended to serve as benchmarks for comparison with existing experimental data. Other primary variables will be the ratio of the column moment capacity to that of the beam and the percentage of transverse reinforcement in the connection. Table 1 summarizes the values of the primary variables for those specimens which have been tested or are under construction. The design and construction of the remaining specimens is awaiting a thorough analysis of the results of the first six specimens. Another important variable when discussing the behavior of beam to column connections is the level of shear stress within the joint. For this test series the joint shear stress will be kept relatively constant between 16 and 20 $\sqrt{f'_c}$.

Preliminary Results. The first four external (E) specimens listed in Table 1 have been tested. First the column was subjected to a constant axial load of approximately forty percent of the balanced axial load and then the beam was loaded according to the displacement controlled loading routine shown in Fig. 1. This loading routine was chosen so the degration of both strength and stiffness with successive load reversals could be studied. The loading routine is more severe than an actual earthquake and displacements similar to those in cycles three through six would be accompanied by story drifts which would compromise the stability of most structures. However, in a laboratory situation it is usually advisable to test a specimen to distruction in order to glean as much information as possible.

The loss of strength in each successive cycle for these four specimens is given in Table 2. Comparisons of specimens 2E and 3E with specimens 1E indicate that increases in only the percentage of transverse reinforcement or only the flexural strength ratio did not significant improve the subassembly behavior. However, increases in both the percentage of transverse reinforcement and the flexural strength ratio lead to a considerable improvement in behavior as shown for specimen 4E.

References:

1. Lee, D.L.N., Wight, J.K., and Hanson, R.D. (1976), "Original and Repaired Reinforced Concrete Beam-Column Subassemblages Subjected to Earthquake Type Loading," Department of Civil Engineering Report No. UMEE 76S4, The University of Michigan, April 1976.

2. Scribner, C.F., and Wight, J.K. (1978), "Delaying Shear Strength Decay in Reinforced Concrete Flexural Members Under Large Load Reversals," Department of Civil Engineering Report No. UMEE 78R2, The University of Michigan, May 1978.

3. "Recommendations for Design of Beam-Column Joints in Monolithic Reinforced Concrete Structures (1976)," Reported by ACI-ASCE Committee 352, American Concrete Institute Journal, Vol. 73, No. 7, July 1976.

4. Meinheit, D.F., and Jirsa, J.O. (1977), "The Shear Strength of Reinforced Concrete Beam-Column Joints," Department of Civil Engineering, Structures Research Laboratory, The University of Texas at Austin, Texas, January 1977.

Table 1 Values of Primary Variables

Specimen Number	Trans. Reinf. in Joint (%)	Flexural* Strength Ratio	Slab and Trans. Beam
1E	0.86	1.1	No
2E	0.97	1.5	No
3E	1.30	1.1	No
4E	1.50	1.5	No
5E	0.86	1.1	Yes
6E	0.97	1.5	Yes
7E	1.30	1.1	Yes
8E	1.50	1.5	Yes
1I	0.76	1.5	No
2I	1.15	1.5	No
3I	0.76	1.5	Yes
4I	1.15	1.5	Yes

*Sum of column Flexural capacities/sum of beam flexural capacities

Table 2 Avg. Max. Beam Load in Cycle/Avg. Max. Beam Load in Cycle 1

Cycle No.	Spec. 1E	Spec. 2E	Spec. 3E	Spec. 4E
1	1.00	1.00	1.00	1.00
2	0.89	0.92	0.95	1.01
3	0.75	0.84	0.84	1.04
4	0.65	0.74	0.73	1.04
5	0.57	0.63	0.60	0.93
6	--	0.54	0.49	0.80

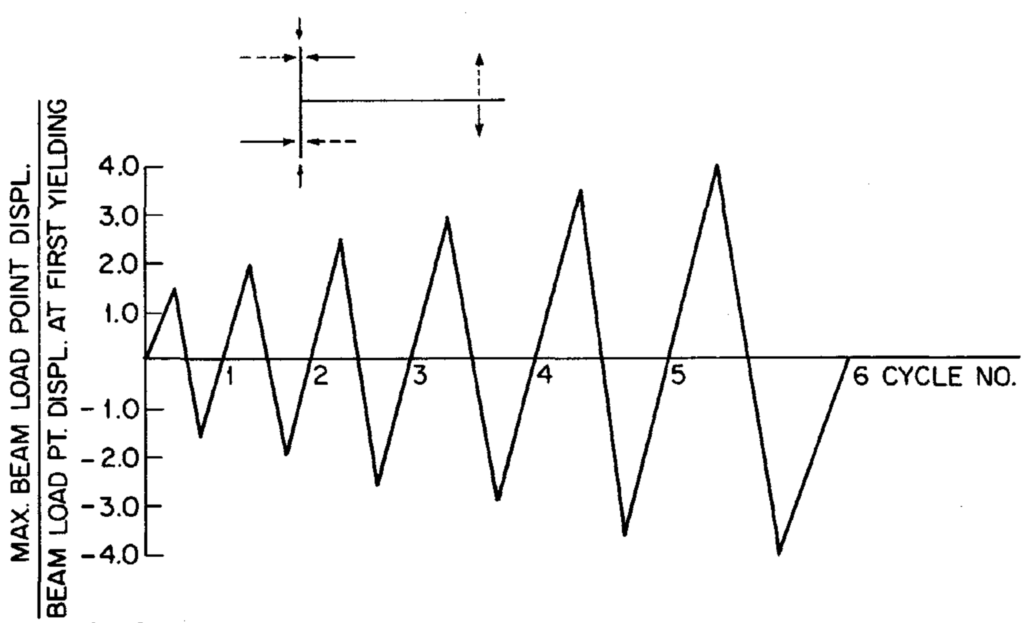


Fig. 1 Beam Displacement Controlled Loading Routine

R. J. Craig

New Jersey Institute of Technology

This paper summarizes current research at New Jersey Institute of Technology which is presently an unfunded project in the structural and concrete laboratory in the area of experimentation for Use of Reinforced Fibrous Concrete in Seismic Areas.

Research Goals

From exploratory research of reinforced fibrous concrete, it has been shown that this type of structure is potentially superior and less costly than the conventional reinforced concrete. The main benefits are increased ductility, increased shear capacity, increased moment capacity, more damage tolerance, and increased tensile capacity. With these beneficial attributes of the reinforced fibrous concrete, these types of structural members would be applicable to seismic area construction. This study is testing the ability of this material to be used in a seismic region.

The study is examining reinforced fibrous concrete structural members in three phases: columns, beams, and joints. The twenty-two column tests are examining the behavior of pure axial loads, compression failure, tension failure, and prue moment with and without fibers of tied columns. The strength and ductility of the columns are of main importance.

The eighteen beam tests are examining the behavior of beams with the combination of fibers and compression steel. The moment-curvature relation is being observed with special interest in non-linear effects. Two-span continuous beams are being tested for the behavior of reinforced fibrous concrete in its ability of redistribution of moment. The nine joint series tests consist of the isolated and interior joints. There are three types of designs being observed: conventional seismic joint, modified seismic joint (no hoops), and partially modified seismic joint (partial hoops). The isolated joints are tested for the flexural critical, and the flexural critical with high shear joints. The interiors are being tested for a flexural critical situation. The joints are loaded with an earthquake representative loading.

The results are being analyzed for theory of analysis and design details of reinforced fibrous concrete. Recommendations are being made to the seismic user groups as to the design, analysis, and construction of this material.

Fibers & Beam Test Series

In this investigation, 18 beams will be investigated. Previous results neglected the presence of compression steel in the beams which is the case found in seismic area structures. From indications of compression test study and tests just explained, the combination of fibers and compression steel will provide a much more ductile and seismic-resistant beams, especially near the joints where hinging occurs. The first 12 beams will look at moment-curvature relationships, deflection and ultimate strength of simple beams with third point loadings. Both mild steel (f_y = 40,000 psi) and high strength steel (f_y = 60,000 psi) will be investigated. Two different steel fibers will be investigated to check the variation of fibers to be used. Then six two-span continuous beams will be loaded with concentrated loads at the center of the spans. These tests will look at the formation of hinges and moment redistribution ability of the beams with the same combinations as were performed by the tests run on the simple beam with third point loadings. The beam test series is graphically displayed in Table I (4 beams only).

In 1979 six of the beams in this test series were constructed and tested in the laboratory. From the results of these tests it has shown that the reinforced fibrous beam is far superior structural to the regular conventional reinforced concrete beams. Some of the results of the moment deflection curve for the single beams test arrangement are shown in Figure I. The presence of fibers increases the ductility and confinement of the concrete in the section. In 1980 the remainder of the test series will be run and data compiled.

Fibers : Column Test Series

This phase will investigate the behavior of fibers in reinforced fibrous concrete columns. There has been little or no work on the benefit of fibers in reinforced concrete columns. From typical stress-strain curves of fibrous concrete, it is evident that the inclusion of fibers will increase the ductility of tied columns which is one of the shortcomings of the failure pattern of these columns. From preliminary tests in our laboratory, the tied column with fibers has a larger capacity for plastic deformation than the conventional tied column. The presence of fibers will also alter the interaction diagram for eccentrically loaded reinforced columns. With the addition of tensile forces after cracking due to the fibers, and increase in ductility in compression, the curves may be altered quite considerably. This study will investigate the changes in the interaction curve and the ductility of tied columns. The presence of fibers will eliminate the brittle failure pattern of tied columns which is typical of these members in seismic regions.

The column tests series will consist of 22 columns. The specimens will be modeled for third scale from prototype. From the model and bond studies conducted from a preliminary investigation, the fibers are being selected to model the 2-1/2 inch long steel fibers in full size columns. The concrete strength will be 5000 psi, and reinforcing will be of Grade 60. Two types of columns will be investigated: one lightly reinforced ($\rho \approx .02$) and one heavily reinforced ($\rho_g \approx .06$). This will represent columns located in upper and lower stories of a building, respectively. The tie spacing will be of conventional design spacing in the columns. A test frame is now being constructed for these tests. Theoretical P-M diagrams for the columns have been developed.

Fibers : Joint Test Series

Two exploratory test joints by Henager[1] demonstrated the feasibility of using steel fibrous concrete in ductile concrete joints. The full size tests showed that a modified joint, using steel fibrous concrete to replace the joint region hoops, had good ductility, was stronger and more damage-tolerant than a conventional ductile concrete joint. The joint also was somewhat stiffer and required fewer stirrups than the reinforced concrete beams. His conclusions were: 1) Initial evaluation of this type of joint of fibrous concrete demonstrates the potential for a superior, less costly joint, 2) Additional evaluations are needed to investigate optimum cost savings by substitution of steel fibers for hoops in building joints 3) Various types and sizes of joints also need evaluation along with development of design methods. (1) A test frame set-up is being constructed. In 1979, a leterature search was started along with preliminary calculations of the sizes of the members and loadings to be expected in the tests. This study will deal with isolated and interior joints (9 specimens) which are constructed in the following manner: 1) Conventional seismic joint, 2) Modified seismic joint (no hoops), 3) Partial modified seismic joint (partial hoops)

This type of construction, reinforced fibrous concrete, has sometimes met with some problems in the field. Thus we are now looking at placing fibrous concrete only in the possible hinging regions to cut down the cost of the fibers and elimination of some construction problems.

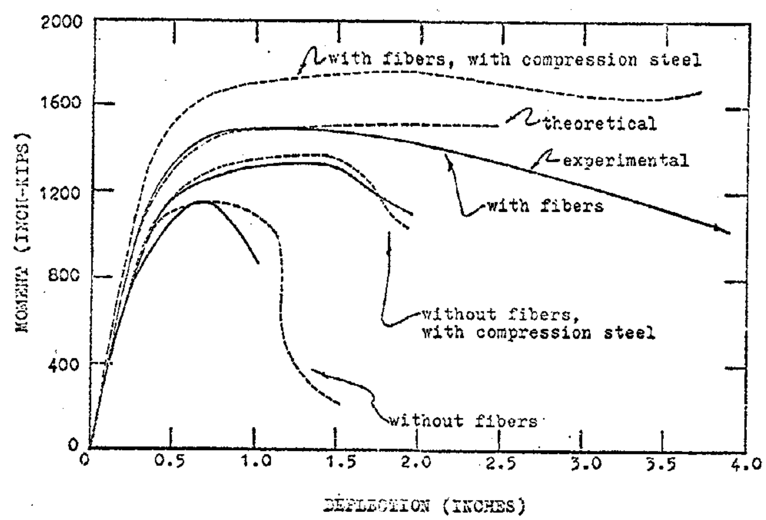


Fig. 1. Comparison of experimental and theoretical moment-deflection curves for test beam series

(1) Henager, C.H., "Steel Fibrous, Ductile Concrete Joint for Seismic-Resistance Structures", ACI SP 53-14; "Reinforced Concrete Structures in Seismic Zones" – 1977 pp. 371-386.

M. L. PORTER AND L. F. GREIMANN

Iowa State University

Synopsis

A research investigation of the earthquake resistance of composite floor diaphragms is being conducted at Iowa State University under the sponsorship of the National Science Foundation. The study involves floor slabs which act as horizontal resisting elements (with in-plane shear) of a building when the structure is subjected to lateral loads caused by earthquake or wind forces. This investigation is a study of one such popular floor slab system, that being steel-deck-reinforced composite floor slabs. A typical steel-deck floor slab with composite support beams is shown in Fig. 1.

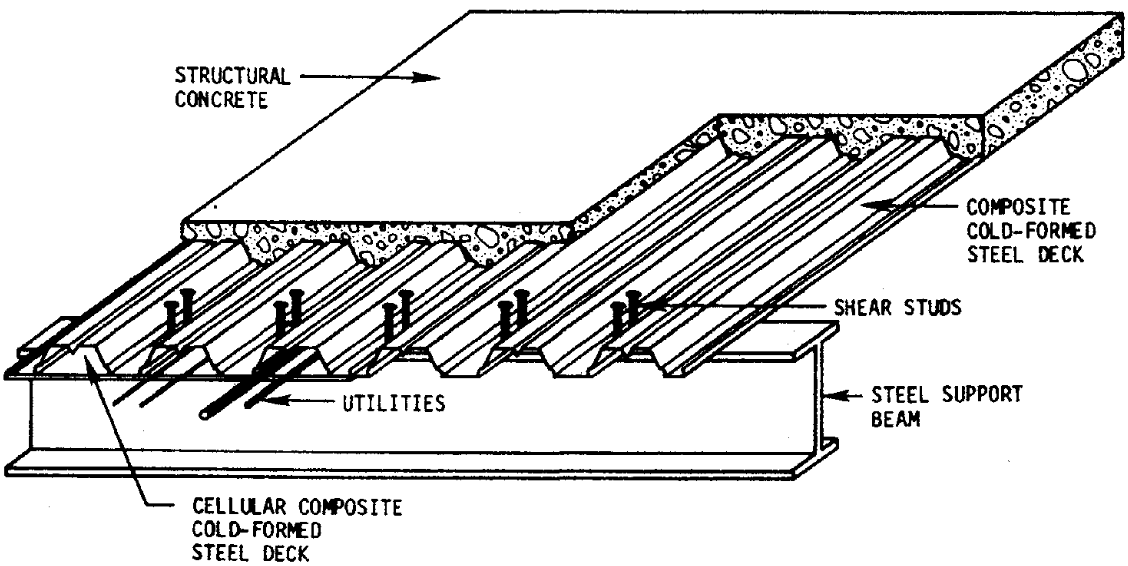


Figure 1. Typical construction utilizing cold-formed steel decking with composite support beams.

Objectives & Scope

The objective of this research is to determine the behavioral and strength characteristics of composite steel-deck floor slab diaphragms. Initial phases of the research include experimental and analytical investigations of the full-scale floor slabs subjected to in-plane shear loading only, followed by later phases to consider combinations of the effects of gravity loading and continuity of adjoining slabs. The initial phases of the program have included 9 full-scale slab specimens measuring 15'-4" by 15'-4" in plan dimensions subjected to in-plane forces, 15 one-way slab elements loaded vertically (gravity), and 41 pushout elements tested with in-plane loading.

The study of the behavioral characteristics include failure mode, degrading stiffness, maximum load capacity, ductility, strain and deformation measurements, crack patterns and other general observations associated with a particular failure mode such as interfacial slip between concrete and steel perpendicular or parallel to the deck corrugations. The purpose of the analytical and experimental phases of the research is to develop recommendations and evaluate significant parameters related to the design of composite steel-deck floor slabs subjected to in-plane shear.

Slab Tests and Associated Parameters

A facility utilizing a cantilever type frame was designed and constructed for the nine full-scale two-way diaphragm slabs tested to date. The primary parameters which varied on these tests were steel-deck type, deck orientation, composite support beam fastener consisting of studs or spot-welds, concrete strength and slab thickness. All other parameters were held constant.

The slabs tested to date followed a displacement program controlled by an MTS closed-loop system. A reverse cyclic displacement program with progressively increasing deflections was used for all slabs except the first pilot specimen which was loaded monotonically.

Three basic modes of failure have occurred, namely:

1. diagonal tension
2. interfacial shear
    a. parallel to deck corrugations,
    b. transverse to deck corrugations, and
3. edge fastener.

Except for the first mode above, tentative analytical procedures have made use of unit strengths and stiffnesses found from pushout specimen tests.

Supplemental Pushout and Vertical Load Tests

Pushout tests have been aimed at determining longitudinal and transverse unit stiffnesses for use in the analytical investigation of the slab diaphragms. The pushout tests investigated strength and stiffness parallel and perpendicular to the steel deck. Also, pushout tests have been conducted for specimens containing stud shear connectors compared with those without connectors. Additional pushout tests are needed, however, to accurately measure the correct stiffnesses.

The 15 vertically loaded specimens were tested to determine the effects of the stud shear connector (used for composite slab-to-support beams connection) capacity on shear-bond strength for one-way slab elements. This stud connector contribution is needed for the interfacial shear slip parallel to the steel-deck corrugations.

Future Investigation

Future experimental and analytical work on this project is anticipated to explore the following areas: perfecting the pushout tests, analytical work involving unit stiffness determinations, investigation of additional parameters effecting the failure mode, slab tests to determine other failure modes, analytical work involving the interlocking frictional forces between steel deck and concrete, analysis of the post-ultimate strength of diaphragm slabs in various failure modes, the analysis and testing of combined vertical (gravity) and in-plane loadings and the effects of continuity of adjoining slab elements.

SOILS & SOIL-STRUCTURE INTERACTION

SUNIL GUPTA AND JOSEPH PENZIEN

University of California, Berkeley

One of the major conceptual and computaional difficulties encountered in the dynamic analysis of soil-structure interaction is the modelling of three-dimensional, semi-infinite soil medium for structures with embedded foundations. A hybrid model is proposed which combines the good features of the currently available methods of analysis while at the same time minimizing the undesirable ones. The modelling is achieved by partitioning the total soil-structure system into a near-field and a far-field. The near-field consists of the structure to be analysed and a portion of the surrounding soil encompassing the complex base geometries of the structure. The far-field is a semi-infinite halfspace with a hemispherical interface common to the near-field. Use is made of the powerful finite element method in modelling the near-field whereas for the far-field an impedance matrix corresponding to the interface degrees of freedom is developed which accounts for the loss of energy due to waves travelling away from the foundation. The proposed model presents a simple but powerful and economical method for the dynamic response analysis of soil-structure interaction effects in three-dimensional embedded structures with flexible foundations.

The development of the far-field impednace matrix, requires the solution of a radiation boundary value problem. For the case of torsional vibrations in axisymmetric problems, it is possible to carry out this rigorous analysis and develop the corresponding impedance matrix. For general three dimensional situations, however, to solve such a boundary value problem appears mathematically intractable at present. For the general case, therefore, a semi-analytical approach is adopted in which the far-field is modelled through continuous three component impedance functions placed at the interface which are then discretized to give nodal impedances at the boundary of the near-field finite element mesh. These frequency dependent impedance functions are obtained through methods of system identification such that the hybrid model reproduces the known compliance functions of a rigid circular plate on an elastic halfspace.

Using the same hybrid modelling approach the method can be extended to cases involving a viscoelastic halfspace, or layered elastic or viscoelastic halfspaces.

G. GAZETAS

Case Western Reserve University

This paper summarizes research that has been conducted over the last one and a half years at Case Western Reserve University in the areas of dynamic response of earth and rockfill dams, dynamic soil-structure interaction, response of soil deposits to various types of waves, and probabilistic methods in soil dynamics.

Dynamic Response of Embankment Dams

Accurate prediction of the dynamic response of earth and rockfill dams during strong earthquakes requires consideration of a number of factors such as the 3-D nature of induced deformations, the inhomogeneity and non-linearity of soil properties and the dam-foundation interaction. But computer and budget limitations of sophisticated methods that can rigorously account for all these factors make the simple 1-D elastic shear-beam model very attractive, at least for preliminary analyses. The goal of this research effort has been the improvement of the shear model to account: 1) for two important variations of the shear modulus of soil(i.e. its increase with the square-root of confining stress and decrease with peak effective shear-strain); 2) for the 3-D chracter of the response due to the geometry of the canyon.

Available results from static finite-element analyses show that the average confining pressure accross a horizontal plane increases approximately in proportion to the 4/3-power of the distance from the crest. Thus G varies according to

$$G(z) = G_m(z/H)^{2/3} \qquad (1)$$

in which G_m = the modulus at the base of the dam, i.e., at z=H. Closed-form solutions were analytically obtained for the natural frequencies, modal displacements or accelerations, modal shear strains and average seismic coefficinets on potential sliding masses of a dam whose modulus varies according to Eq. 1 and is built in rectangular canyon (psuedo 3-D geometry). The method has been successfully evaluated through extensive comparisons with the recorded response of actual earth and rockfill dams (in Japan, USA and Europe) during earthquakes or man-induced vibrations. Results will soon appear in publications [1] and [2]. Research is currently underway to account for soil non-linearity, a more realistic (truly 3D) canyon geometry, and dam-foundation interaction.

Stiffness of Foundations on Soil Consisting of Heterogeneous Layers

So far dynamic stiffness functions of foundations have been analytically obtained only for soils consisting of a number of homogeneous layers, i.e. with wave velocities that remained constant throughout each layer. Continuous variation of velocities with depth is of interest not only with soils whose stiffness depends on the effective overburden pressure and the degree of overconsolidation (both functions of depth within a layer), but also with rocks adjacent to excavations, for which the degree of induced loosening decreases with distance below the surface of excavation.

An analytical-numerical formulation has thereby been developed to obtain dynamic stiffnesses as functions of frequency of rigid strip foundations resting on a multilayered halfspace. Each layer is characterized by an S-wave velocity that increases or decreases linearly with depth, i.e.,

$$c=c_o(1+bz) \tag{2}$$

where the rate of heterogeneity b can be any real number, positive or negative; a constant Poisson's ratio ν=o.25; and a constant density. For such a medium, the equations of motion can be transformed into two uncoupled equations in terms of pseudo-dilatational and pseudo-distortional wave potentials, Φ and Ψ, defined by

$$\{d\}=G\nabla(G^{-1}\Phi)+G^{-1}\nabla x(G\cdot\Psi) \tag{3}$$

where $\{d\}=\{u,w\}^T$ is the displacement vector. Solving in closed-form the two uncoupled equations and imposing the 'exact' boundary conditions at the layer interfaces and the top surface, solutions are obtained for the swaying, rocking and vertical stiffnesses of an infinitely stiff or infinitely flexible strip footing having 'rough' or 'smooth' contact surface with the soil ('complete' or 'relaxed' boundary). Results have so far been presented [Publ. 3] for two characteristic soil profiles (halfspace and stratum-on-rock) and an interesting equivalence has been established between heterogeneous and homogeneous media. Other characteristic soil deposits are also under investigation (Publ. 4]

Response of Soil Deposits to Body and Surface Waves

Several theoretical studies and recorded strong motion data have demonstrated that in the frequency range of interest in earthquake engineering surface and nearly-horizontal body waves often dominate the ground motion at medium and long epicentral distances. The objective of the reported research was two-fold: 1) Using analytical wave-propagation theories to systematically compare the effects of Rayleigh, Love and inclined body waves to those of vertical shear waves on the dynamic reponse (displacements and stresses) of a variety of realistic soil deposits; and 2) to evaluate the ability of the wave propagation theories to interprete the spatial distribution of acceleration time histories recorded during actual earthquakes.

The theoretical studies [Publ. 5] have shown that Rayleigh and vertical S-waves produce similar attenuations with depth of horizontal motions, for periods close to or greater than the first natural period of the deposit in vertical S-waves; the two types of waves, however, yield different distributions of shear stresses with depth and induce different motions of the soil particles. Field evaluation of the various soil-response theories was performed using the motions recorded underground (in borehole accelerometers) during several earthquakes at two sites in the Toyko Bay area, in Japan. These studies [reported in Publ. 6] have illustrated the importance of the "wave content" of ground shaking (i.e., of the various types of waves and their angle of incidence) on the variation of accelerations and stresses with depth below the surface. Additional studies of this type are underway using four strong motion surface accelerograms recorded in Thessaloniki, Greece, during the 1978 earthquakes of June 20 (M=6.5, R-20km) and July 4 (M=5, R=20km).

Random Vibration Analysis of Earth Dams

This research effort started only a few months ago and is conducted in collaboration with Professor Dario Gasparini (see his summary for details). A state-space random vibration formulation is expanded to study the seismic safety of earth dams. Using a non-stationary filtered noise as input excitation, evolutionary r.m.s. values and probability distributions of accelerations, stresses, permanent sliding deformations and liquefaction damage in earth dams can be obtained. The first results will appear shortly [Publ. 7 and 8]. Overall objective of the research is to develop simplified, inexpensive, random-vibration-based method(s) to assess the seismic safety of various types of dams, accounting for the key features of their reponse and the most important sources of uncertainly.

Publications

1. Gazetas, G., "SHEAR VIBRATIONS OF VERTICALLY INHOMOGENEOUS EARTH DAMS", Int. J. for Num. & Anal. Meth. in Geomechanics (submitted, Jan. 1980).

2. Gazetas, G., "3-DIMENSIONAL LATERAL AND LONGITUDINAL SEISMIC STABILITY OF EARTH AND ROCKFILL DAMS", Proc. 7th WCEE, Istanbul, 1980.

3. Gazetas, G., "STATIC AND DYNAMIC DISPLACEMENTS OF STRIP FOUNDATIONS ON HETEROGENEOUS MULTILAYERED SOILS", Geotechnique, Vol. 30, No.2, 1980.

4. J.R. Newmark & G. Gazetas, "VIBRATIONS OF FOOTINGS ON DEPOSITS CONSISTING OF AN OVERCONSOLIDATED CLAY CRUST FOLLOWED BY DEEP SOFT CLAY", (in preparation).

5. Gazetas, G. & Yegian, Y, "SHEAR AND RAYLEIGH WAVES IN SOIL DYNAMICS", Proc. ASCE, Vol. 105, GT12, 1979.

6. Gazetas, G. & Bianchini, G., "FIELD EVALUATION OF BODY AND SURFACE-WAVE SOIL AMPLIFICATION THEORIES", 2nd U.S. Nat. Conf. Earthq. Eng., Stanford, 1979.

7. Gasparini, D., DebChaudhury, A. & Gazetas, G., "RANDOM VIBRATION ANALYSIS OF SHEAR BEAMS", Int. J. of Earthq. Eng. & Str. Dyn. (submitted).

8. Gazetas, G., DebChaudhury, A. & Gasparini, D., "RANDOM VIBRATIONS ANALYSIS OF EMBANKMENT DAM DEFORMATIONS", (in preparation).

YIH-HSING PAO

Department of Theoretical and Applied Mechanics, Cornell University

Under the sponsorship of the International Program of the National Science Foundation, the author visited the National Taiwan University(NTU), Taipei, Republic of China in 1978-79 and conducted research on the interaction of seismic wave and foundations. The research was done jointly with Professor C.S. Yeh of the Department of Civil Engineering and the Center for Earthquake Engineering Research of NTU and his associates. In addition, the author organized a Workshop on Earthquake Engineering and invited 16 specialists from local universities and engineering consulting firms to lecture on 19 topics for three weeks. The topics are essentially those contained in the book "Introduction to Earthquake Engineering" by S. Okamoto, which was tranlated from Japanese and English into Chinese by the lectures. More than 100 engineers participated in the Workshop.

Theoretical studies of the interaction of seismic wave with foundations were made on the basis of scattering of elastic waves by an inclusion in an infinite, and a half space. These and other problems investigated are discussed in the following:

<u>Interaction of Ground Shock with a Circular Cylinder</u>

A surface shock moving with a super-seismic speed will induce two plane waves in the ground. When the secondary scattering from the cylinder to the surface of the ground is neglected, the problem is reduced to that of oblique incidence of plane pulse on a circular cylinder. Analysis is first performed for the Fourier components of the incident pulse (a plane harmonic wave) and the final result is obtained by Fourier Synthesis.

Although the solution for the scattering of plane harmonic elastic waves (P or SV wave) by a circular cylinder in an infinite space has been obtained many years ago (see Ref. 1), no detailed information on stresses or strains is available. Calculations were made for radial and axial stresses in the cylinder and for the resultant bending movement at a cross section. Our results show that during the passage of an obliquely incident P-wave, a significant amount of bending stresses is developed in the buried cylinder.

This investigation was done jointly with F.C. Moon and A. Ceranoglu of Cornell University prior to the visit to Taiwan.

<u>Interaction of Seismic-Wave with an Inclusion in a Half Space</u>

Because of the additional reflection from the plane boundary, the scattering of elastic waves by an inclusion in a half-space is much more complicated than that in an infinite space. For inclusion with circular cylindrical geometry, analysis can be made by iterating the multiple scattered waves which are expressed in series expansion of cylindrical wave functions [2]. For inclusion with arbitrary geometry, the method of transition matrix [3] and the method of boundary integral equation (BIE) [4] can be applied.

The method of series expansion of wave functions was tried to determine the solution of the scattering of P-wave by a semi-circular cavity in a half-plane. In addition to providing the dynamic stress-concentration factor around the cylindrical surface, the solution furnishes the dynamic influence coefficients at the semi-circular boundary of an embedment [5].

Since the method of wave function expansion is limited to inclusions with circular or spherical geometry, the other two methods mentioned previously were also explored. The method of BIE was found more suitable to calculate the wave field near the inclusion, especially that at the boundary.

The formulation of the boundary integral equation for the wave field at the surface of a scatterer in an infinite space is well known [4] (ch. 2 of[1]). For an inclusion embedded in a half-space, it is only necessary to change the kernel function for an infinite space (Green's function) of the integral equation to that for a half-space. For a SH-wave in a half-space, the kernel function is easily obtainable, and the boundary integral equation is being solved numerically.

Kernel functions for P and SV waves in a half-space (Lamb's problem) are also available. The functions, however, are so complicated that whether the integral equation can be solved effectively is uncertain. Investigation is still in progress.

The research described in this section has been conducted jointly with C.S. Yeh and his associates at NTU.

Other Investigations

Other problems related to soil-foundation interaction were also investigated jointly with the research group at NTU. Two investigations are near completion: (1) The dynamics of the dam-reservoir interaction, and (2) The amplification of ground waves by a hill.

In case (1), the reservoir is filled with a layer of sedimentation. For a muddy layer, it is modeled by a liquid with a density much heavier than that of the overlaying water, and a Westergaard type solution is obtained. When the sedimentation is composed of sand and large aggregates, it is modeled by an elastic solid layer. The solution is no longer so simple and the investigation is still in progress. If successful, it will also provide an answer to the dynamic interaction of soil and retaining wall.

In case (2), the one dimensional wave equation for rod or shear beam with variable cross-sections is used to study the converging of longitudinal or transverse waves from the bottom to the top of a hill. The approach is similar to that by Shahinpoor *et al*. [6] which was found after the completion of the project. Numerical results (not given in Ref. 6) showed that the ground acceleration at the top can be many times larger than that at the bottom of the hill.

References

[1] Y. H. Pao and C.C. Mow, Diffraction of Elastic Waves and Dynamic Stress Concentrations, Crane and Russak, New York, 1973.

[2] R. D. Gregory, "An Expansion Theorem Applicable to Problems of Wave Propagation in an Elastic Half-Space Containing a Cavity," Proc. Cambridge Philos. Society, v. 63, p. 1341, 1967.

[3] Y. H. Pao, "Betti's Identity and Transition Matrix for Elastic Waves," J. Acoustical Soc. America, v. 64, p. 302, 1978.

[4] V. D. Kupradze, "Dynamic Problems in Elasticity" in Progress in Solid Mechanics, v. 3, edited by I. N. Sneddon and R. Hill, North-Holland, Amsterdam, 1963.

[5] C. S. Yeh, J. Penzien, and T. W. Lin, "Dynamic Response of an Embedded Structure," in Modern Problems in Elastic Wave Propagation, edited by J. Milowitz and J. D. Achenbach, Wiley-Interscience, New York,1978.

[6] M. Shahinpoor, I. G. Tadjbakhsh and G. Ahmadi, "Seismic Response of Hills," Iranian Journal of Science and Technology, v. 6, p. 199, 1977.

CHING SHUNG CHANG

University of Massachusetts

This paper summarizes current research at the Department of Civil Engineering at the University of Massachusetts sponsored by the National Science Foundatin in the area of earthquake hazards mitigation. The objective of the study was to develop a design method for footing settlement resulting from earthquake induced pore pressure. The invesigation considered: (1) the deformation characteristics of soil under cyclic loading, (2) the characteristics of pore pressure development in undrained soil samples during cyclic loading.

Pore Pressure Development. A number of models for predicting pore pressure build-up during cyclic loading have been studied. Based on the laboratory cyclic test data of undrained sand samples, the adequacy of different models was evaluated. For practical purposes, the model recently proposed by Finn, et al.* seems to provide a reasonable prediction of the magnitudes and the trends of pore pressure build-up of sand samples under cyclic loading, in which the samples were anisotropically consolidated. Nevertheless the results of the comparison between test data and model prediction also indicate that the model proposed by Finn, et al. has some practical and theoretical limitations. In particular, for samples under higher consolidation ratio the model is not applicable. In our study, improvement was developed to extend the model's applicability to samples consolidated under general anisotropic stress conditions. The extended model was varified by laboratory tests.

Residual Deformation During Cyclic Loading. The residual deformation characteristics of undrained soil samples under cyclic loadings have been investigated. A five-parameter stress-strain model was developed for predicting soil undrained residual deformation. The model accounts for the effects of general anisotropic consolidation stresses, magnitude of cyclic stresses, and stress path. The model shows excellent agreement between measured and predicted residual deformations of sand samples.

Footing Settlement Due to Earthquake. The problems of footing settlement due to an earthquake are currently being studied in detail in order to (1) develop a methodology to predict pore pressure build-up and accompanying residual deformation of soil under a footing during the earthquake, and (2) develop an analytical tool to evaluate the resulting settlement due to the dissipation of the earthquake-induced pore pressure. The research effort will be devoted to integrating the previously described research results and results from pertinent sources including seismology and soil-structure interaction. An analytical model will be used for predicting footing settlement and the results compared with observed damage. The method can be used as a design guideline for earthquake resistant foundation design.

*W.D. Liam Finn, K.W. Lee, C.H. Maartman, and R. Lo, "Cyclic Pore Pressure Under Anisotropic Conditions," Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference, Earthquake Engineering and Soil Dynamics, June 1978, p. 457-472.

G. A. ATHANASOPOULOS AND F. E. RICHART, JR.
University of Michigan

Current research at the University of Michigan concerning "Time Effects on Dynamic Properties of Cohesive Soils" is sponsored by the National Science Foundation.

Objective

It is the objective of this investigation to evaluate the time effects which produce a significant influence on the shear modulus and damping of cohesive soils. Initial studies have used Vac-Aire extruded samples of kaolin, but emphasis will be placed on studying the behavior of natural samples. The time effects to be considered include: (a) time of sustained confining pressures, (b) strain rate during loading, (c) rest intervals between loadings, (d) loading patterns, (e) load-time pulse shape, and (f) loading amplitudes.

Test Procedures

The principal tests used for evaluating changes in shear modulus and damping are the resonant column tests. The influence of the various time effects on the low-amplitude shear modulus and damping are studied using four Hall - type and one Hardin - type resonant column devices. Influences on large-amplitude values of shear modulus and damping are evaluated using a Drnevich - type (Model 1) and a new (July, 1979) Drnevich Long-Tor type resonant column device. All of these devices, except the Long-Tor, are described in reference (1). Geonor triaxial test equipment provides for isotropic or anisotropic preconsolidation of samples which are then tested the resonant column machines. The Hardin device has been modified to permit variations in axial loading on the sample proir to, or during, dynamic testing.

Preliminary Results

Low-amplitude dynamic tests on the Vac-Aire extruded samples were run on normally consolidated, and isotropically and anisotropically preconsolidated samples. It was found that creep developed during anisotropic states of stress influenced the secondary phase of the low-amplitude shear modulus (G_o) vs. log time diagram. This influence was negligible for creep stress levels less than about 30% of $(\sigma_1 - \sigma_3)_f$, but becomes important as the stress level is increased. During one series of tests at a level of 60% of $(\sigma_1 - \sigma_3)_f$, the secondary time effect was eliminated and a horizontal line was developed on the G_o vs. log time diagram. Additional data are accumulating.

(1) "Vibrations of Soils and Foundations", by Richart, Hall, & Woods, Prentice-Hall, Inc. Englewood Cliffs, N.J. (1970)

MUSTAFA ERDİK and METE ÖNER

Earthquake Engineering Research Institute
Middle East Technical University, Turkey

Introduction

One of the current earthquake engineering research topics at the METU/EERI, Turkey, is the experimental and analytical treatment of the dynamic soil-structure interaction problem. Earthquake Research Institute of the Ministry of Reconstruction and Resettlement provides partial financial support for these studies.

This report summarizes the results of the forced vibration tests on a prefabricated panel type structure and comparisons with theory. Similar type of buildings resting on different soils are being tested and analyzed with the objective of developing simplified rules that are to be refected in the new version of the Turkish Earthquake Resistant Design Code.

Experimental Studies

The experimental setup used consists mainly of a rotating mass type vibration generator, control unit, accelerometers and recorders. The vibration generator was mounted on the floor of the top storey, and the frequency of excitation was varied from about 1 to 10 cps. Resonance curves were drawn from the results of the response measurements to find natural frequencies, mode shapes and damping ratios. A detailed description of the testing procedure may be found in Çelebi et al (1977).

Fig. 1 shows the floor plan of the 7-storey building tested and the locations of the instruments. The direction parallel to the longer side of the building is identified as "P direction and the other as "D direction." For vibrations in the latter direction, a resonant frequency of about 3.8 cps. and a damping ratio of about 13% were obtained for the first mode. In the former direction corresponding values were 3.6 cps and 7%.

Analytical Studies

For a simplified response analysis, the structure was assumed to be a rigid body resting on an elastic half space. The method developed by Öner and Janbu (1976) was employed to calculate a representative (equivalent) shear modulus for a given soil-structure system. This method considers the confining pressures due to both the body weight of the soil and the additional stresses created by the static foundation pressure.

Details of the calculations and comparisons with obsirvations may be found in Öner and Erdik, 1980. Resonant frequencies and amplitudes were found to agree quite well. Fig. 2 shows a comparison of the observed and predicted fundamental mode shapes.

Conclusions

For a box type panel structure resting on a medium to soft foundation soil, dynamic soil-structure interaction effect was found to be dominating the response under vibration testing conditions. From a comparison of the measured frequency, mode shape and damping characteristics with those predicted by a simple "rigid structure-flexible soil" idealization, it may be concluded that

1. The dynamic response of such a structure depends strongly on the foundation soil characteristics rather than the details of the structure, and

2. Natural frequencies, mode shapes and damping ratios for this type of a structure may be calculated reasonably accurately by the proposed simple two degree of freedom system, provided that the required equivalent dynamic properties of the soil are properly assesed.

It is clear that research along this line must continue to provide more data to substantiate these arguments. It is also essential to include soil nonlinearity in the analyses to cover strong earthquake ground shaking conditions, since this type of low-cost housing seems to develop rapidly in the seismic regions of the World.

References

Çelebi, M., Erdik,M., Yüzügüllü,Ö. "Vibration of a Ten Storey Reinforced Concrete Structure" METU/EERI Report No. 77-1, 1977, Ankara.

Öner,M., and M.Erdik, "A Case Study of Dynamic Soil-Structure interaction," Proc. International Conference on Engineering for Protection from Natural Disasters, Bangkok, Thailand, 1980.

Öner,M., and Janbu,N., "Nonlinear Analysis of Foundation Vibrations", 2nd Int. Conf. on Numerical and Analytical Methods in Geomechanics, Virginia, Vol.2, 1976, pp. 1025 - 1037.

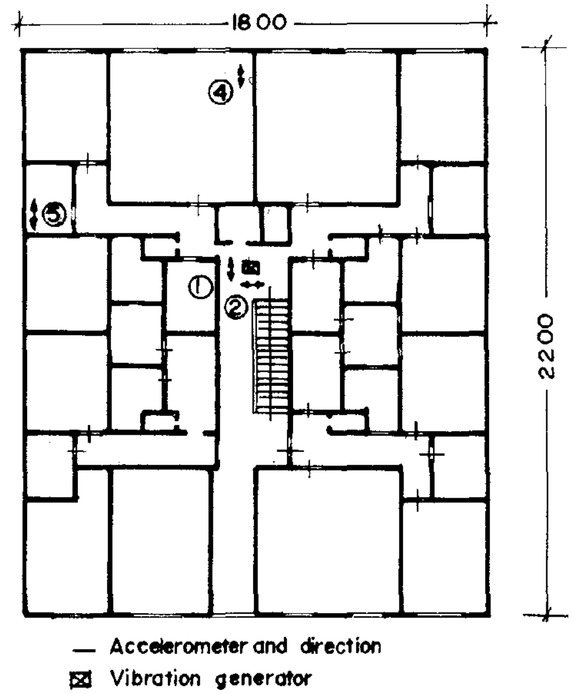


FIG. 1. FLOOR PLAN AND INSTRUMENT LOCATIONS

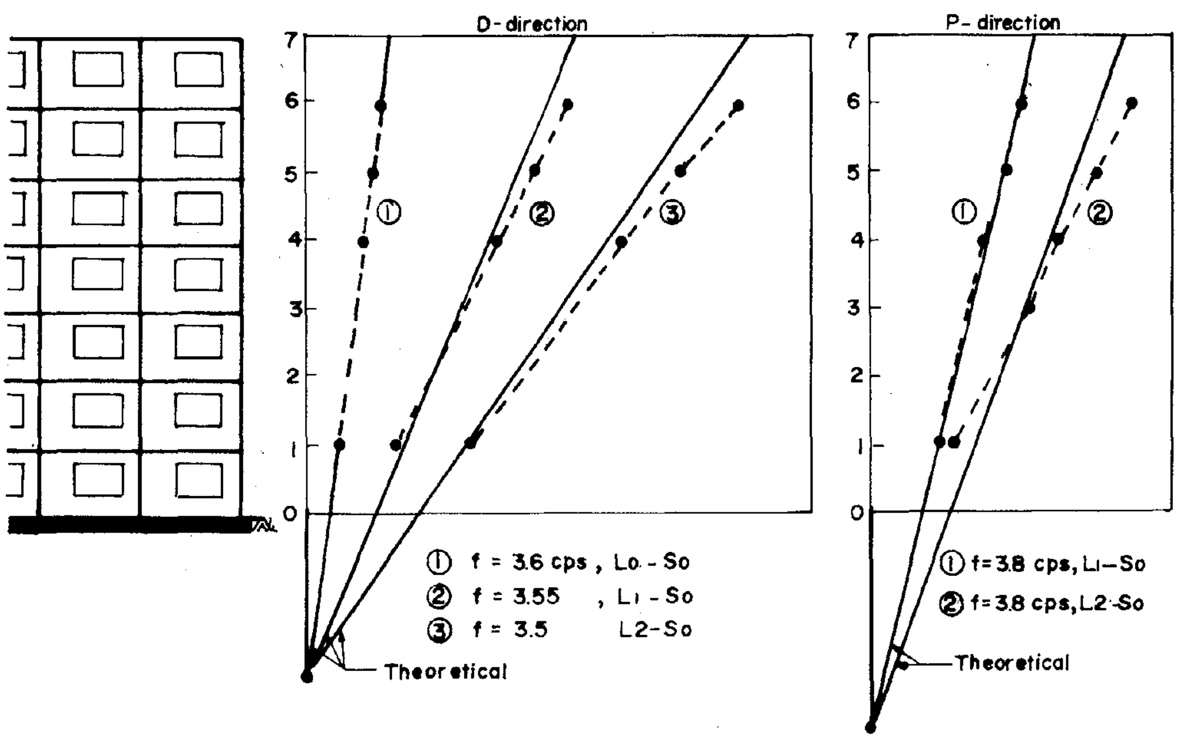


FIG. 2. OBSERVED AND PREDICTED FUNDAMENFAT MODE SHAPES

PEDRO A. DE ALBA

University of New Hampshire

Research in soil dynamics at the University of New Hampshire is concentrating on the problem of soil liquefaction under earthquake loading. Two studies are currently under way; one refers to the behavior of piled foundations in a liquefying deposit, and the other to the use of acoustic techniques in evaluating soil liquefaction potential.

Pile Behavior in Liquefying Soils

Little is known about the effect of earthquake-induced pore-water pressure increase on the bearing capacity of piles driven into saturated sand. A model study of this problem has been funded by NSF under the Research Initiation in Earthquake Hazards Mitigation program.

For this study, a specialized simple-shear type machine has been designed to test 22-in. dia. cylindrical sand specimens into which one or more model piles can be "driven". Figure 1 is a schematic of this device, which is undergoing final debugging at the time of this writing. Cyclic shear loading is applied at the base, which moves on low-friction rollers; the top cap is attached to a rigid reaction frame. Lateral confinement is provided by a stack of rigid steel rings. During cyclic loading these rings will slide over each other, generating complementary cyclic shear stresses on the vertical surface of the sample, thus completing a correct simple shear loading.

The 1-in. diameter model pile is contained in a case attached to a rigid bar buried in the upper part of the specimen. This pile can be drawn out of its case after confining pressure is applied, by means of a fine wire attached to the tip of the pile as shown. This method of insertion, as opposed to merely burying the pile in the sample, should produce a stress distribution which more closely simulates that which is obtained by pile driving. Variables that will be monitored in each test include pore-water pressure buildup during shaking, pile displacement and applied shear loading.

Single-pile tests will be carried out at two relative densities: 50% and 70%; and will also study the effects of sequences of small shocks followed by a larger event, as well as of different effective confining pressures in the 20 to 40 psi range. Scaling effects will be considered by using piles of different diameters. Finally, based on the results of the single-pile tests, a test series is envisaged using a group of four piles.

Liquefaction Potential by Acoustic Techniques

Laboratory tests by various researchers have shown that the liquefaction resistance of sand samples measured in the laboratory is sensitive to such factors as sample preparation method; age of the sample at the time of the test; sequences of low level cyclic loading before applying failure loading; and sample preconsolidation. Such differences are attributed to differences in sand fabric produced by different preparation methods and stress histories. These fabric effects are largely destroyed by conventional sampling techniques.

The general reasoning behind this project is that, if fabric determines the mechanical properties of the sand, the transmission of acoustic signals through different fabrics must be affected in a characteristic way for each case.

If characteristic "acoustic signatures" can be developed for a field deposit, they may be used to reconstitute disturbed samples in the laboratory to their correct fabric. Liquefaction tests can then be performed on samples which are close to the true field deposition conditions.

As a first step, a feasibility study was carried out, funded by the Leslie and Iola Hubbard Fund of the University, to determine whether laboratory specimens prepared by different methods could be identified using simple compression-wave transducers. Figure 2 shows results obtained by transmitting 240 kH_z compression waves longitudinally through saturated 2.8 in. dia. sand samples 7 in. long. Tamped samples were built up in layers, whereas poured samples were made by continuous pouring from a flask with a calibrated opening. It may be seen that the tamped samples show consistently lower peaks of the power spectra of the transmitted signals. Work is currently under way using both shear and compression waves to study acoustic behavior of samples prepared by the same method but subjected to different stress histories.

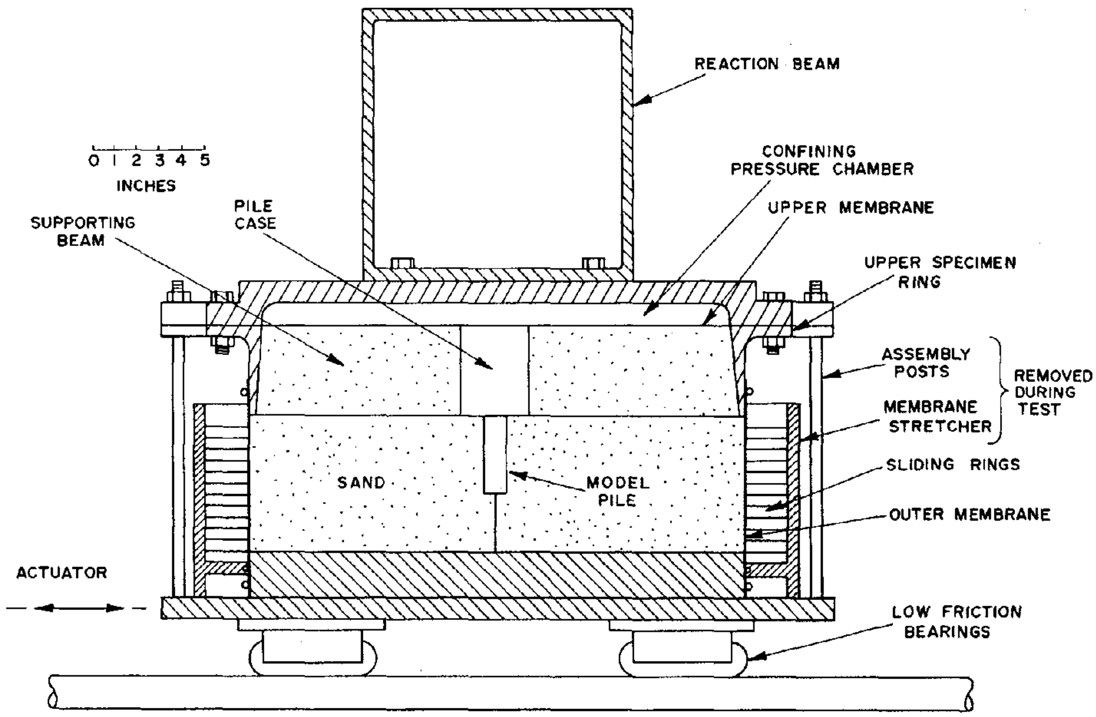


FIG. 1. SECTION OF PROPOSED SIMPLE SHEAR DEVICE

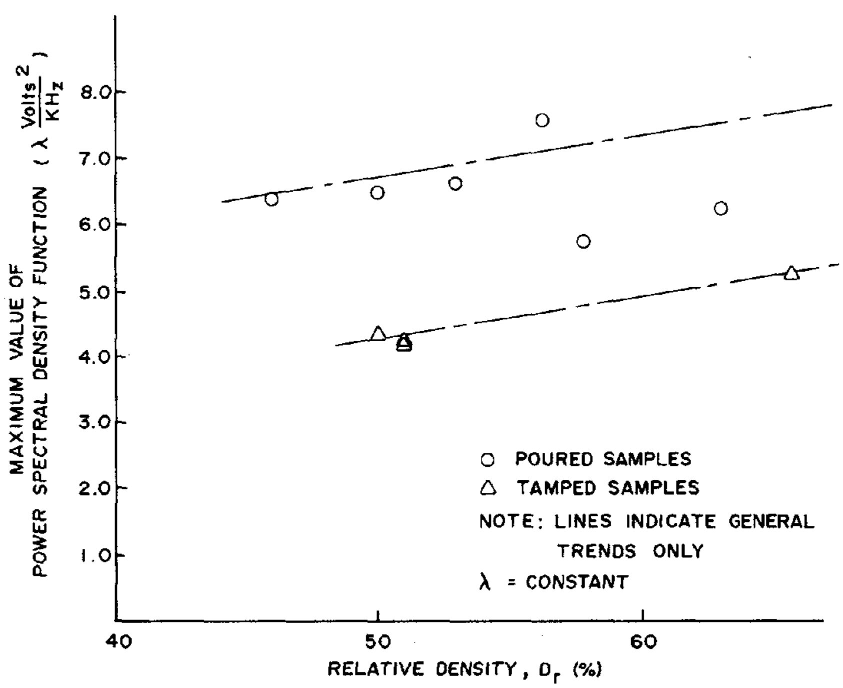


FIG. 2. COMPRESSION WAVE TEST RESULTS

TED S. VINSON

Oregon State University

Introduction

Early research to evaluate the dynamic properties of frozen soils was associated with engineering problems in Alaska and other cold regions of the world arising in connection with (1) vibrating machinery placed on or in frozen ground deposits, (2) geophysical exploration of frozen ground deposits and (3) excavation of frozen ground deposits by blasting. Later, the need to evaluate the dynamic properties of frozen soils under simulated earthquake loading conditions was recognized in environmental situations where permafrost deposits existed in highly seismic regions of the world. Examples of areas with substantial permafrost and high seismicity include the central portion of Alaska and the Baikal region in the U.S.S.R.

More recently, however, the demand for energy has focused attention on the need to evaluate the dynamic properties of frozen soils under earthquake loading conditions even in temperate climates. Underground liquefied natural gas storage tanks are being constructed in highly seismic areas of the world such as Japan. A zone of frozen soil several meters thick can develop around the tank. A hypothetical zone is shown in Figure 1. An accurate analysis of the tank requires a determination of the dynamic properties of the frozen soil surrounding the tank under simulated earthquake loading conditions.

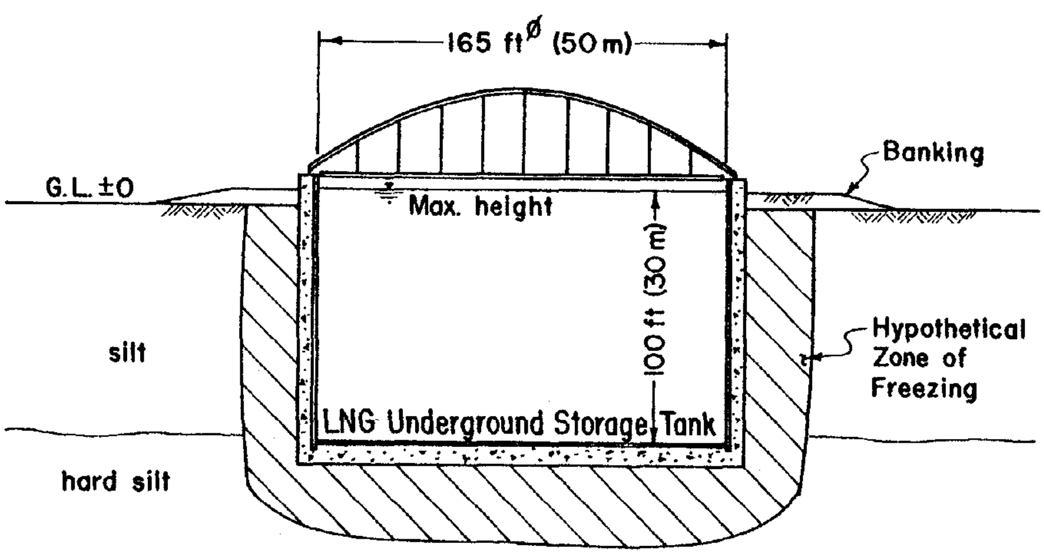


Figure 1. LNG Underground Storage Tank with Hypothetical Zone of Freezing at Negishi Base, Japan

Research Goals and Program

In response to the need to evaluate the dynamic properties of frozen soil under simulated earthquake and low frequency loading conditions, National Science Foundation research is being conducted to:

(1) determine the dynamic properties of naturally frozen soils over the range of test conditions associated with wave propagation problems of frozen soil deposits (e.g., foundation vibrations, geophysical exploration, blasting, ground response analyses during strong motion earthquakes);

(2) investigate parameters that might influence the dynamic properties of naturally frozen soils such as soil type, soil density, nature of the ice phase, anisotropy, temperature, confining pressure, confinement duration, thermal history and amplitude, frequency and duration of dynamic loading;

(3) develop design equations or curves to evaluate the dynamic properties of naturally frozen soils based on a knowledge of index and classification parameters.

In the research program specimens obtained from approximately 150 naturally frozen soil samples taken in situ from Alaska will be tested with both resonant column and cyclic triaxial equipment. Resonant column testing is nondestructive. Consequently, the specimen will first be tested with this equipment and, immediately following, it will be tested with cyclic triaxial equipment. Values of complex Young's and shear modulus, phase lag, Poisson's ratio, dynamic Young's modulus and damping ratio will be measured. Anisotropic effects for the frozen soils will be investigated by testing samples which were cored in the vertical, horizontal, and inclined (45°) direction in the field at the same location. The information obtained from the overall program will be used to develop an understanding of the significance of various material and test parameters on dynamic properties of naturally frozen soils. Finally, the dynamic properties measured will be combined with the existing body of information on dynamic properties of frozen soils to establish design equations or curves suitable for use with existing analytic techniques to solve wave propagation problems. The goal of this work is to allow scientists and engineers to establish representative values of dynamic properties for frozen soils based on a knowledge of the material and test parameters previously mentioned and other index and classification parameters.

Summary of Progress to Date and Relation to Proposed Work

Under NSF Grant ENG 77-04437 the following progress was made:

(1) A 12 ft (3.7 m) x 14 ft (4.3 m) x 8 ft (2.4 m) walk-in Cold Room Test Facility (CRTF) was designed and fabricated. The CRTF is used for sample storage, test specimen preparation and dynamic testing. The CRTF has two alarm systems which indicate when the temperature rises above a set level and signals research personnel of the alarm condition.

(2) A resonant column test system capable of both longitudinal and torsional excitation was designed and fabricated. The test system is contained inside a triaxial cell to allow a confining pressure to be applied. The test system is used inside the CRTF.

(3) A cyclic triaxial test system to apply a cyclic deviator stress to a test specimen was designed and fabricated. The test system is contained inside a triaxial cell to allow a confining pressure to be applied. The test system is used inside the CRTF.

(4) An environmental chamber was designed and fabricated to control the test specimen temperature during resonant column or cyclic triaxial testing. The environmental chamber allows temperature control to ± 0.2°C.

(5) An industrial lathe and drill press were modified to allow naturally frozen soil test specimens to be obtained from larger diameter core or block samples.

(6) Approximately 35 ft (11 m) of 9 in. (23 cm) diameter frozen soil core samples were shipped from cold storage in Oakland, California, to Oregon State University for storage in the CRTF.

(7) Approximately 250 ft (76 m) of 3 in. (8 cm) diameter frozen soil and ice core samples and nine 10 in. (25 cm) x 10 in. (25 cm) x 30 in. (75 cm) frozen soil blocks were taken in the Fairbanks area, Alaska, and shipped to Oregon State University for storage in the CRTF.

(8) Design equations were obtained for dynamic properties of nine artificially frozen soil types and ice. The dynamic properties were obtained under a previous NSF contract. The dynamic equations reflect the influence of several parameters.

Under NSF Grant CME-7919697 resonant column and cyclic triaxial tests are presently being conducted on naturally frozen silts. Over the next two years, the research program previously described will be conducted.

M. G. SHARMA AND S. SHARIATZADEH-RAFIE

The Pennsylvania State University

Considerable literature is available on a variety of laboratory and field techniques for evaluating dynamic soil properties and dynamic soil behavior. The characteristic properties that have been evaluated using these techniques are mostly the dynamic moduli (both Young's and shear modulus), damping and attenuation.[1]* These properties are determined by assuming, in general the material behavior as linear. Under earthquake loading conditions, soils may be subjected to high stresses that may produce large deformations and non linear dynamic response. In order to analyse this response, it is very important to have a knowledge of non linear dynamic constitutive properties.

This paper is concerned with the evaluation of nonlinear dynamic properties of a cohesive soil. As part of this study cylindrical samples were subjected to cyclic uniaxial compressive stress superimposed on a mean uniaxial compressive stress and the resulting uniaxial strain was measured for various frequencies ranging from 1 to 40 hertz, large range of stress amplitude and mean stress. Figure 1 shows the experimental set up used in the study. From the experimental data, the dynamic compliance versus frequency and the hystersis loop curves were obtained (see Figs. 2 and 3).

For the soil tested the dynamic mechanical behavior has been modelled using the nonlinear viscoelastic theory as developed by Green and Rivlin.[2] An examination of data indicates that three kernel functions are required to describe the nonlinear dynamic constitutive properties of the test material. Using the developed Kernel functions, the energy loss per cycle was evaluated and compared with the corresponding value obtained experimentally. The comparison was found to be good.

Presently, the study is being extended to higher stress magnitudes, larger frequencies and several moisture contents. The behavior is also studied under a large range of confining pressures.

Acknowledgement: This research is funded by the National Science Foundation under Grant No. PFR-7823098

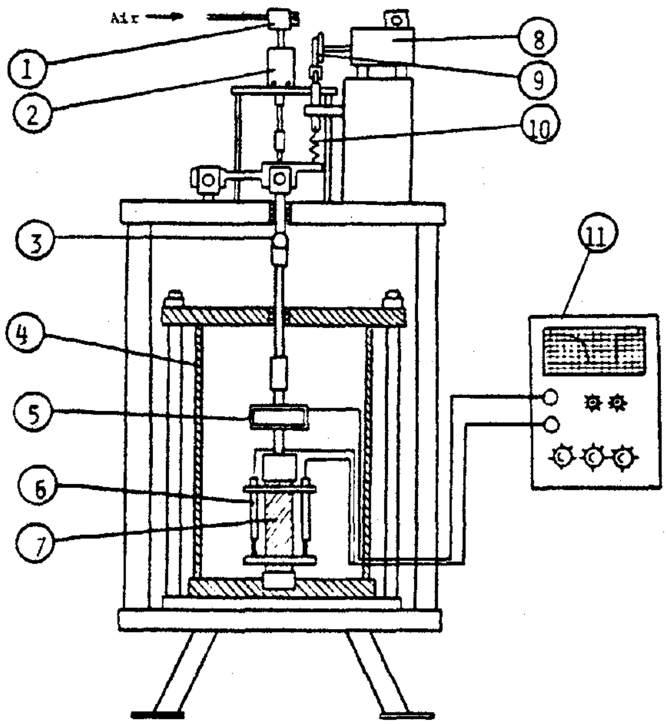
References

[1] Woods, R. D., Measurement of Dynamic Soil Properties, Proceedings ASCE Geotechnical Engineering Division, Specialty Conference - Earthquake Engineering and Soil Dynamics, Vol. I, June 19-21, 1978, Pasadena California, pp. 91-178.

[2] Green, A. C. and Rivlin, R. S., Mechanics of Nonlinear Material with Memory. Archives for Rational Mechanics and Analysis, 1:1-21 (1957).

---

*The number in the bracket refer to bibilography at the end.



1- mac-valve
2- bellofram
3- a 3/4" steel ball
4- plexi-glass cylinder
5- load cell
6- LVDT
7- soil specimen
8- variable speed motor
9- eccentric system
10-spring
11-amplifier & recorder

Fig. 1- Schematic diagram of dynamic soil testing apparatus.

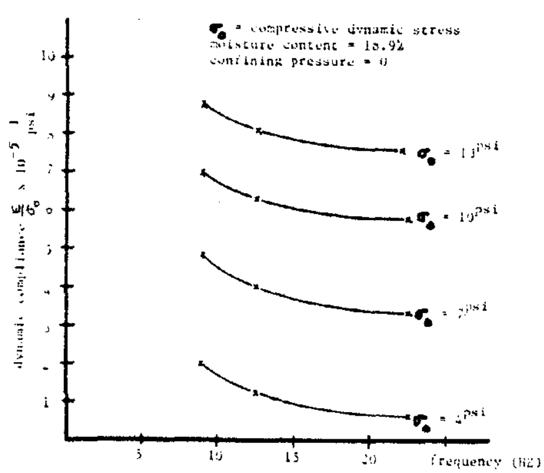


Fig. 2- Variation of dynamic compliance with frequency for a cohesive soil.

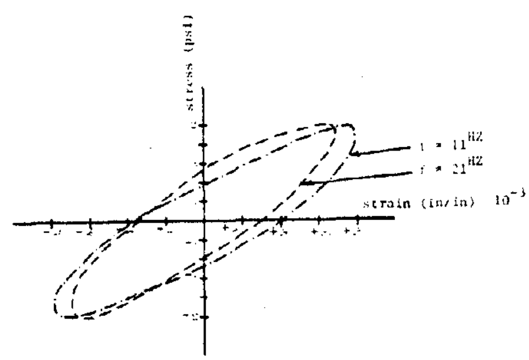


Fig. 3- Typical stress-strain hysteresis loops for a cohesive soil under cyclic compressive stress.

L. L. CHU, A. M. ABDEL-GHAFFAR, A. ASKAR, A. S. CAKMAK

Princeton University

Following is a brief report on a comprehensive study which is in progress; the study is part of earthquake engineering research activities in the Department of Civil Engineering at Princeton University. In this study a new solution technique is being developed for elastodynamic problems: (1) Wave-Structure Interaction (elastic waves scattering) and (2) Soil-Structure Interaction. The first topic and a preliminary stage of the second are being studied with the support of the School of Engineering and Applied Science at Princeton University; the second topic is in the proposal stage and has been submitted to the National Science Foundation.

New Solution Technique for Elastodynamic Problems

The Born approximation, a procedure that is widely used in quantum mechanics for scattering theory but not well known in elastodynamics, is being used to achieve an iterative solution technique. The method is based on the integral representation of elastodynamics equations in a form that admits an iterative solution within the spirit of the Born approximation. Through this iterative solution, which can be carried out in principle to any desired level of accuracy, no equation, either for the motion on the inclusion or for points on the surface, has to be solved, and only volume and surface integrals over the inclusion in the infinite-space or foundation or canyon in the half-spaces need to be evaluated. In addition, the method requires only a Green's function for the differential operator irrespective of the boundary conditions.

Wave-Structure Interaction (Elastic-Wave Scattering)

In the wave-structure interaction the scattering problem is examined for incident waves approaching at various angles; both cavities and inclusions are studied.

Two cases are examined for the inclusion: (1) cavity (unlined or lined) and (2) rigid (fixed or movable). Some results (by the approximate method) for anti-plane SH-waves scattered by circular cylinders in the infinite-space are shown in Fig. 1 where they are compared to the exact solutions obtained by separation of variables and series expansion. In all cases of inclusion it is observed that the near as well as far field solutions are quite accurate for $ka \leq 1$, where k is wave number and a is the radius of inclusion. In this range of wave numbers it is seen that the second order Born approximation brings a significant improvement. For the global motion of the rigid body an excellent agreement is observed for almost all wave numbers. This result however is explainable in terms of the exact series expansion. Therefore, it seems that the method is a reasonable approximation for relatively low-frequency wave-scattering problems. In addition, for the far-field a larger range of validity for the approximation is observed. Hence, the far-field solution can be utilized as rational boundary conditions for the refined finite element calculation for the near-field.

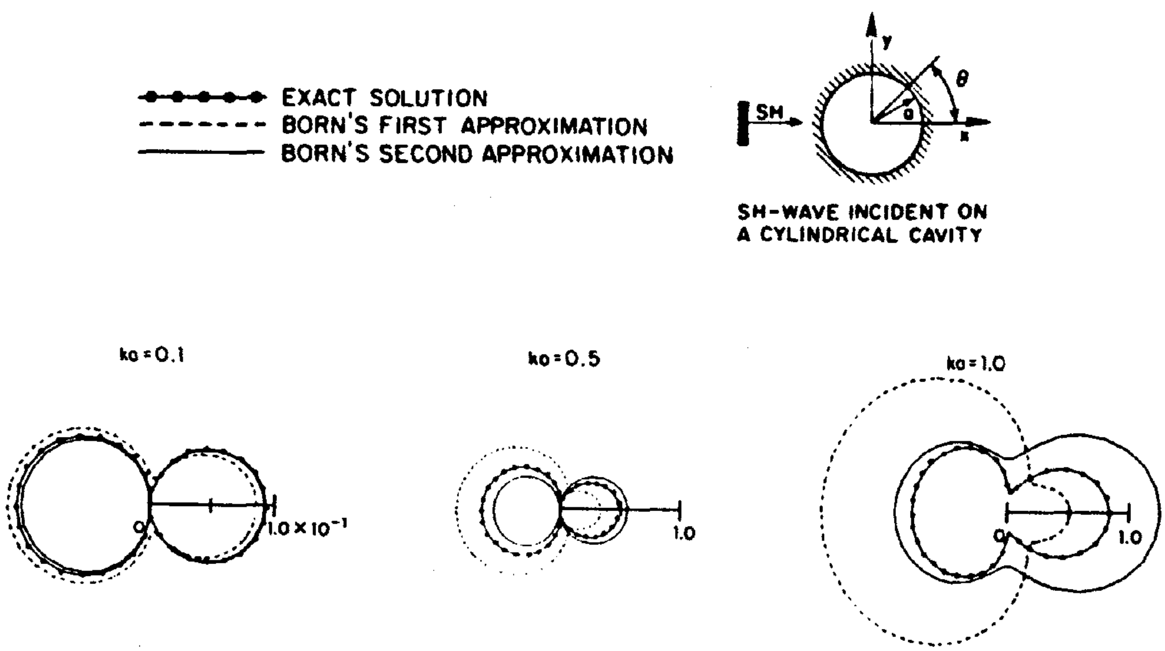
Soil-Structure Interaction

A wide class of two- and three-dimensional problems involving foundations of regular or irregular shapes and incident SH-, SV-, P-, and R- (Rayleigh) waves at any angle of incidence can be solved efficiently by the approximate approach. In addition, the technique can be used to obtain the far-field results which in turn can be coupled with existing finite element solutions in order to provide realistic soil-structure interaction boundary conditions. The method can also be coupled with the equivalent linearization scheme or perturbation technique to solve non-linear soil problems.

As a preliminary study, the technique is used to solve the soil-structure interaction 2-D problem of a shear wall welded to a semi-circular rigid foundation in the half-space. Some of the results are shown in Fig. 2 where they are compared to the closed form existing solutions. An excellent agreement is observed for almost all wave numbers.

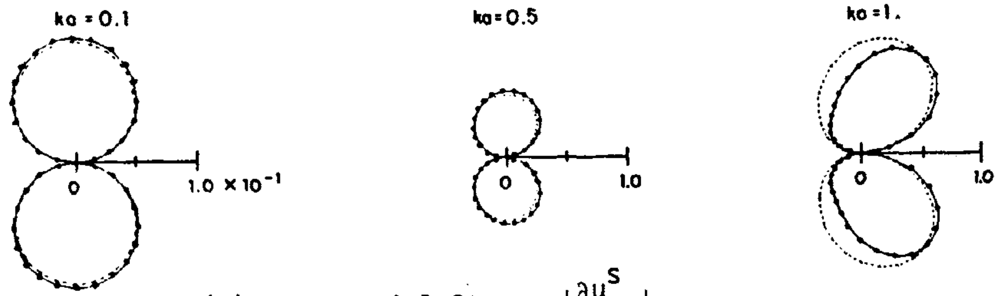
Current Publication

Chu, L. L., Cakmak, A. S., Askar, A., "Born Approximation for Wave Scattering in Elastodynamics," to be presented at the ASME Century 2-ETC, San Francisco, CA, August 12-15,1980.

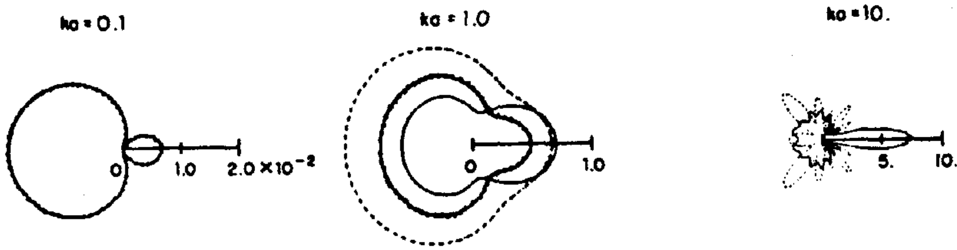


(a) Displacement at the boundary $|u^S(\underline{x}_0)|$ vs. θ

Fig. 1 Scattering of SH-Waves by Circular Cavity

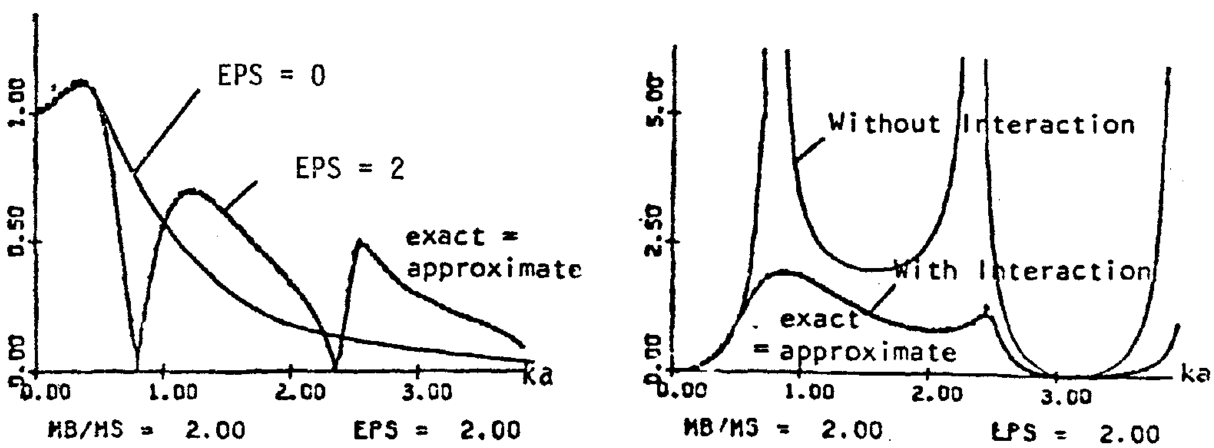


(b) Tangential Stress $\left|\frac{\partial u^s}{\partial r}\right|$ vs. θ



(c) Scattering Coefficient at Far-Field

$|\sqrt{k'}\,\psi_s|$ vs. θ



(a) (b)

Fig. 2 Foundation Displacement and Relative Response of Shear Wall on a 2-D Semi-circular Foundation Subjected to SH-Waves

JEAN H. PREVOST and A. CEMAL ERINGEN

Princeton University

The Department of Civil Engineering at Princeton University is investigating a rigorous and complete formulation for soil as a multiphase medium for the study of liquefaction phenomena, and is currently seeking funds from the National Science Foundation to support this research.

Research Needs

Liquefaction occurs in loose or medium-dense saturated cohesionless soil deposits whose tendency to compact is accompanied by an increase in pore-water pressure when subjected to undrained or partly-drained monotonic and/or cyclic loading conditions. The resulting pore-water pressure gradients in the soil cause movements of the water from the soil voids.

The various analytical methods presently used to evaluate liquefaction potential of in-situ soil deposits have several shortcomings. The most important ones are their extensive empiricism and their restriction to one-dimensional situations which prevent their extension to the two- or three-dimensional field situations. Furthermore, the methods are inconsistent since their use linear mechanical field equations, together with nonlinear material constitutive laws. Indeed, it must be noted that all studies reported so far are nothing else than arbitrary "nonlinearized" versions of basically linear formulations. Only a rigorous fundamental formulation of soil behavior under dynamic loading conditions can introduce in a consistent manner observed coupling effects, and account for the multidimensionality of the phenomena involved.

Research Plan

The objectives of this research are:

(1) To derive the nonlinear coupled field equations which describe transient phenomena in saturated porous media.

(2) To derive realistic multidimensional, constitutive equations which describe the behavior of the soil skeleton when subjected to complicated three-dimensional, and in particular, to cyclic, loading paths.

(3) To use the theory to study boundary value problems of interest in geotechnical engineering which involve saturated soil deposits.

In this study, soil is viewed as a two-phase medium consisting of a porous solid skeleton interacting with the pore water filling the voids. Some noticeable progresses have already been made in this research, as reported in Refs. [1] and [2].

References

[1] Prevost, J.H., "Mechanics of Continuous Porous Media," Int. Jnl. Eng. Science, 1980 (to appear).

[2] Provost, J.H., "Consolidation of Anelastic Porous Media," Jnl. Eng. Mech. Div., ASCE, 1980 (in process).

JEAN H. PREVOST and ROBERT H. SCANLAN

Princeton University

The Department of Civil Engineering at Princeton University is investigating the feasibility of performing dynamic soil tests in a centrifuge, and is currently seeking funds from the National Science Foundation to support this research.

Research Needs

A centrifuge can simulate gravity-induced stresses in soils at a reduced geometrical scale through centrifugal loading. This modeling technique leads to a set of scaling relationships which show the usefulness in using a centrifuge to test large structures, and to test soil and soil-structure interacting systems under dynamic loading conditions. However, only a few dynamic tests have been reported so far in the literature. This may be due to a number of difficulties associated with performing dynamic soil tests in a centrifuge, as follows:

(1) *Dynamic Scaling Laws:* It is generally convenient to carry out tests at scales of about 1/100, so that the model must be subjected to 100 g centrifugal acceleration. At this scale, the natural frequencies of the model, and the simulated earthquake vibration frequencies are 100 times those of the prototype. Model earthquake durations are 100 times shorter than those in the real world, and accelerations, of course, are 100 times larger. Thus, for example, at this scale, a model vibration analogous to one of the components of the well-known 1940 El Centro record would have a duration of a few tenths of a second and would involve a peak acceleration of about 35 g. If, for structural analysis purposes, real earthquake frequencies up to 10 Hz are to be taken into accout, then the model earthquake should include frequencies of up to $10 \times 100 = 1$ kilo Hz., i.e., in the audio range. The development of an adequate vibration input capability for centrifuge testing is therefore necessary.

(2) *Boundary Effects:* The velocity of wave propagation in soil is the same in both model and prototype situations. Wave velocities of the order of 1000 ft/sec are thus to be dealt with in centrifuge experiments. This immediately raises questions about boundary effects and reflection-refraction type phenomena in dynamic centrifuge tests. Thus, for example, if a dynamic test is to be performed in the center of a 24 in. square bucket filled with soil, dynamic waves will reach the sides of the bucket after 1/1000 s and, if reflected, will interact with the experiment after 2/1000 s. Such effects could prove most detrimental to soil-structure interaction studies which may involve frequencies up to 1 kilo Hz. The development of an adequate vibration isolation capability for the soil container is therefore necessary.

(3) *Recording Equipment:* Because of the high frequencies involved in dynamic tests performed in a centrifuge, the necessary recording and

data processing equipments are most sophisticated. If for example, frequencies of 1 kilo Hz are to be recorded, the recording equipment must be able to collect and store data at least every 1/3000 s.

Research Plan

In order to assess the feasibility of performing dynamic soil experiments in a centrifuge, research is being conducted in the following areas:

(1) Investigation of the free and forced vibration response of single piles embedded in soil deposits of the appropriate type.

(2) Development of vibration isolation capabilities.

This involves investigation of acoustical absorption and wave trap devices with the aim of attenuating to the maximum, the inevitable traveling waves arriving at the interior boundaries.

Whether or not waves typical of the action being duplicated can be effectively trapped and/or attenuated within the limited space available near the bucket boundaries is a major question of this portion of the research. However, a number of accoustical attenuation devices, such as multiple wedges, isolation chambers, absorptive material, etc., are being examined.

If, for example, a typical wave velocity is 1000 ft/sec and a typical frequency is 1 kHz, a wave of length of 1 foot must be effectively attenuated at the test boundary. If such wavelengths can be reduced by raising the key frequencies of the experiment, it may be possible to achieve effective devices to trap them, using a number of well known approaches from acoustics.

On the other hand, if the acoustic reflection or stress-wave problem proves to be exceptionally recondite, knowledge of this fact and its implications for the validity of dynamic measurements through centrifuge testing will offer an important contribution to the future art of such testing.

W. F. CHEN and S. L. KOH

Purdue University

This paper summarizes current research at Purdue University sponsored by the National Science Foundation in the area of analytical studies on earthquake-induced landslides. The ultimate objective of this research is to devise the means and develop the capabilities for the proper assessment of the danger of slope failures and landslides. A valid assessment of this hazard requires the complete progressive failure analysis of specific soil slope problems under static and dynamic loading conditions. In turn, this requires the application of suitable constitutive relations which describe the basic characteristics of the soil under the different types of loads.

The current research is basically directed toward a better understanding of the close interaction between soil properties on the one hand and, on the other hand, the instability and subsequent slope failure that results from a seismic disturbance. While various types of constitutive models for soils have been developed in recent years for use in earthquake engineering, the relative advantages and disadvantages, the limitations and ranges of applications of these models have not been assessed critically, particularly as they apply to soil instability problems.

In the first part of the study, emphasis is made on the critical assessment of existing soil constitutive models from the viewpoint of experimental and theoretical consideration as well as the application of these models in numerical calculations solving specific benchmark problems. On the basis of this assessment, improved constitutive models have been developed and refined following the basic approach of the theory of plasticity. The improved models have been used to re-interpret and re-evaluate available data from laboratory tests to verify the adequacy of the improved models for general use in earthquake-induced landslide calculations. Ultimately, the new knowledge generated will be useful in formulating criteria for the choice of sites for slopes, in the design of man-made slopes, and in providing a basis for disaster prediction.

Summary of the Work

At present, the analysis and design of slopes against earthquakes is based mainly on accumulated experience as laid down by empirical rules. However, the necessity of developing better capabilities and methods for the proper assessment of the danger of slope failure and landslides based on a rational theory is urgently needed. The classical theory of plasticity constitutes a general framework for such development. The present work focuses on the use of several plasticity models for the seismic analysis of slopes.

There exist a number of plasticity models which reflect some important features of soil behavior. The complexity of soil behavior in a natural slope and the variation of test data from conventional tests make the selection of a suitable model difficult. Therefore, some idealization is in order to make the mathematical analysis tractable.

The current investigation of the dynamic response of soil slopes is based on three types of plasticity models: (1) elastic-perfectly plastic, Coulomb-type model, for in-plane collapse analysis (extended pseudo-static method of limit analysis of perfect plasticity); (2) elastic-perfectly plastic, Drucker-Prager model for a complete progressive failure stress analysis; and (3) elastic-strain-hardening plastic, cap model for a complete but a more refined analysis of progressive failure.

The first model is viewed as a useful model for developing a "simple" procedure for practical use. The second model is considered as a useful computational tool but not as a highly accurate predictor of detailed soil stress-strain behavior. It provides some necessary verifications of the results of the first model and it builds up the necessary groundwork for the implementation and further development of the more refined third model. The third model is viewed as a sophisticated research-oriented model that the consulting engineer may not find immediately useful for everyday use. However, it provides the analytical basis for the methods to be developed using the "simpler" models.

Schedule of the Work

The work on the behavior of slopes subjected to seismic loads can be grouped according to the particular type of plasticity model used:

1. Perfect Plasticity of the Coulomb Type:
    a. Method: pseudo-static limit analysis
    b. Formulation:
        i. non-uniform seismic coefficients for collapse analysis (complete).
        ii. rigid-body displacement calculations (in progress).
        iii. dynamic effects on soil shearing resistance (in progress).
    c. Application: field benchmark problems (future).
    d. Design: simplified charts (in progress).
    e. Computer Program: (in progress).

2. Perfect Plasticity of the Drucker-Prager Type:
    a. Method: finite-element procedure
    b. Formulation: classical plasticity (complete).
    c. Application: typical configuration (in progress).
    d. Design: comparative study with the limit analysis results (in progress).
    e. Computer Program: (in progress).

3. Strain-Hardening Plasticity of the Cap Type:
    a. Method: finite element procedure
    b. Model Evaluation:
        i. experimental data (complete).
        ii. analytical consideration (complete).
        iii. numerical consideration (in progress).
        iv. empirical expressions for modulus (in progress).
    c. Formulation: general three-dimensional stress-strain equations (complete).

d. Application:
   i. typical configurations (in progress).
   ii. field benchmark problems (future).
e. Design: comparative studies with the previous solutions (in progress).
f. Computer Program: (in progress).

Publications and Related Activities

1. Chen, W. F., Chang , C. J. and Yao, J. T. P., "Limit Analysis of Earthquake-Induced Slope Failure", Proceedings, 15th Annual Meeting of the Society of Engineering Science, Edited by R. L. Sierakowski, University of Florida, pp. 533-538, 1978.

2. Chen, W. F. and Koh, S. L., "Plasticity Approach to Landslide Problems", In: S. L. Koh (Editor), Mechanics of Landslides and Slope Stability, Engineering Geology, Elsevier, 1980, to appear.

3. Chan, S. W., Chen, W. F. and Koh, S. L., "Limit Analysis of Seismic Slope Stability", Proceedings, 7th World Conference on Earthquake Engineering, Ankara, Turkey, September 8-13, 1980, to appear.

4. Chen, W. F., "Plasticity in Soil Mechanics and Landslides", Journal of the Engineering Mechanics Division, ASCE, Vol. 106, EM No. 3, June, 1980, to appear.

5. Chen, W. F. and Mizuno, E., "On Material Constants for Soil and Concrete Models", Proceedings, 3rd Engineering Mechanics Division Specialty Conference, ASCE, The University of Texas at Austin, September 17-19, pp. 539-542, 1979.

6. Chen, W. F., Invited Predictor for the NSF/NSERC North American Workshop on "Plasticity and Generalized Stress-Strain in Soils" McGill University, Montreal, May 28-30, 1980.

7. Chen, W. F., An Invited General Paper Entitled "Effect of Plasticity Models on the Response of Soil Slopes" for the Symposium on "Implementation of Computer Procedures and Stress-Strain Laws in Geotechnical Engineering", Virginia Polytechnic Institute and State University, August 3-6, 1981.

8. Chang, M. F. and Chen, W. F., "Lateral Earth Pressure on Retaining Walls Subjected to Quasi-Static Earthquake Forces", to be presented at the Session on "Limit Equilibrium Plasticity Applications in Geotechnical Engineering", ASCE Florida Convention, October 27-31, 1980.

9. Mizuno, E. and Chen, W. F., "Analysis of Slopes with Different Plasticity Models", to be presented at the Session on "Generalized Stress-Strain Application in Geotechnical Engineering, ASCE, Florida Convention, October 27-31, 1980.

10. Koh, S. L., Organizer, Two Sessions on "Soil Dynamics", 16th Annual Meeting, Society of Engineering Science, Northwestern University, September 5-7, 1979.

D. A-GRIVAS

Rensselaer Polytechnic Institute

The objectives of this NSF sponsored project are: (a) to provide a probabilistic model for the assessment of the safety of earth slopes under earthquake loading, and (b) to apply the developed model to a number of case studies reflecting the seismic characteristics of the State of New York. A short description of the tasks pursued in achieving these objectives is the following:

1. Probabilistic Seismic Stability Analysis

To develop a model for seismic stability analysis, significant uncertainties associated with conventional pseudo-static methods are recognized and probabilistic tools are introduced for their description and amelioration. In particular, the present model accounts for (a) the variability of material strength parameters, (b) the uncertainty in the exact location of potential failure surfaces, and (c) the uncertainty in the value of the maximum slope acceleration during an earthquake.

The soil material comprising the slope is assumed to be probabilistically homogeneous with strength parameters (c and $t=\tan\phi$) being beta distributed random variables. Potential failure surfaces are considered to have an exponential shape (log-spiral), defined with the aid of three random variables (two geometric parameters and the frictional component of soil strength). The safety of the slope is measured in terms of its probability of failure (p_f), the numerical values of which are obtained through a Monte Carlo simulation of failure.

The seismic load is introduced into the analysis through the maximum horizontal ground acceleration (a_{max}) experienced by the slope during an earthquake. It is assumed that a_{max} is a random variable, the probability distribution of which depends on the earthquake magnitude (measured in Richter scale),the type of earthquake source (i.e., point, line, or area source), the distance between the source and the site, and a number of regional parameters.

References

The following two NSF reports describe the details of this task:

1. A-Grivas, D., J. Howland, and P. Tolcser, "A Probabilistic Model for Seismic Slope Stability Analysis", Report No. CE-78-5, Dept. of Civ. Engr., RPI, Troy, N.Y., 12181

2. A-Grivas, D., "Program RASSUEL - Reliability Analysis of Soil Slopes under Earthquake Loading", Report No. CE-78-6, Dept. of Civ. Engr., RPI, Troy, N.Y., 12181

2. Seismicity of New York State

An engineering analysis is performed of the seismic history of New York State. Data on earthquakes which affected the State have been compiled, evaluated and statistically analyzed. The resulting list contains 1289 seismic events that took place in the period between 1568 and 1975. A log-quadratic frequency-magnitude relationship appears to best represent the available data. This is shown in Figure 1.

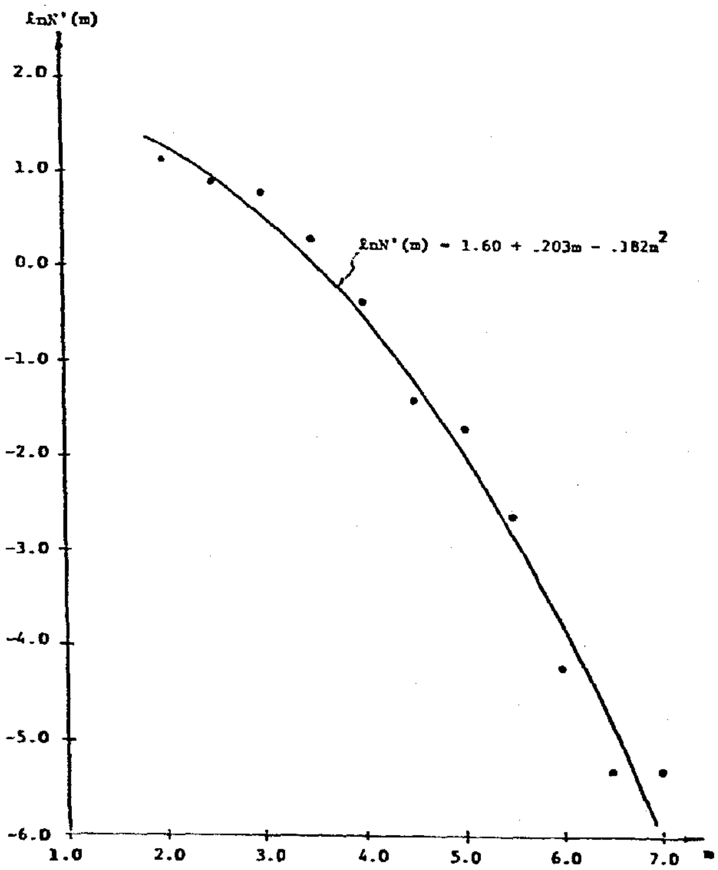


Figure 1. The Quadratic "Best Fit" Relationship between Magnitude and Recurrence of Earthquakes for the 407 - Year Period.

The seismic hazard that corresponds to the log-quadratic frequency-magnitude relationship is determined for a number of return periods and under the assumption that earthquakes occur in accordance with the Poisson model. The case where earthquakes follow a more general Markov process is also investigated. As an example, Figure 2 shows a comparison of the seismic hazards that correspond to the Poisson and Markov models.

Reference

The following NSF report describes the details of this task:

A-Grivas, D., R. Dyvik and J. Howland, "An Engineering Analysis of the Seismic History of New York State", Report No. CE-78-7, Dept. of Civil Engr., RPI, Troy, N.Y., 12181

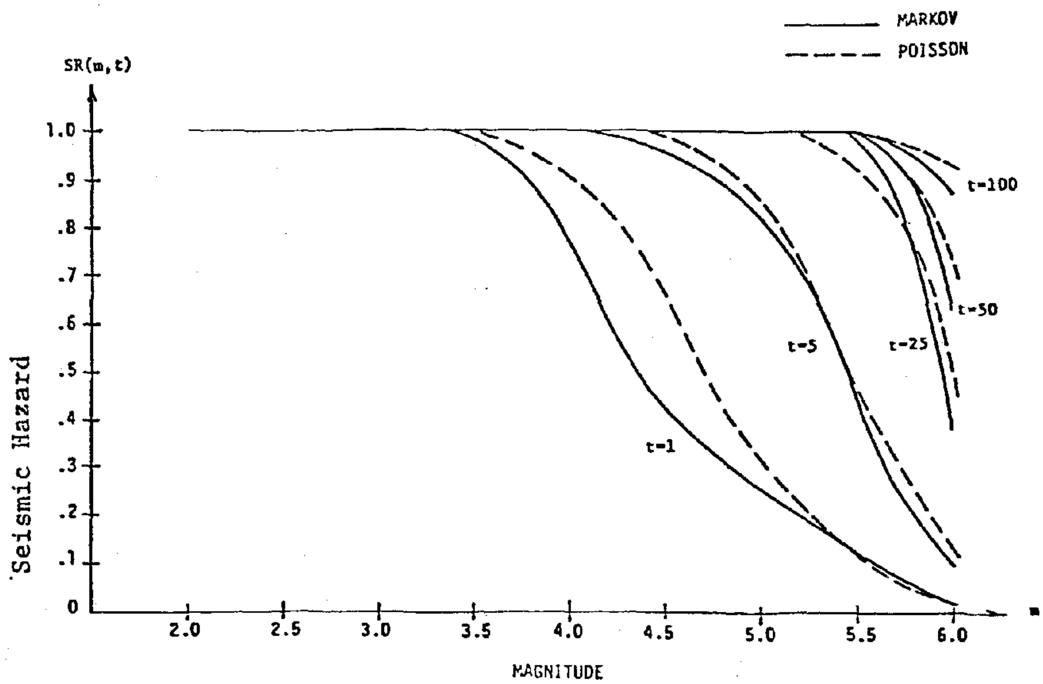


Figure 2. Comparison of Seismic Hazard for Poisson and Markov Models - Based on the Data for the last 50 Years (1925-1975)

3. Application of Model

The developed model is used to provide a probabilistic seismic stability analysis to a natural slope located near Slingerlands, New York. Three types of possible earthquake sources are investigated, namely, a point, a line and an area source. The dependence on significant seismic parameters of the probability of failure of the slope is examined and the results are presented in a number of graphs and tables. Among the conclusions drawn from this study are the following: (a) the present model is useful in assessing the reliability of soil slopes under both static and seismic conditions, and (b) the probability of failure of a soil slope is greatly affected by the type of earthquake source involved and the values of the seismic parameters that are associated with it.

Reference

The following NSF report describes the details of this task:
A-Grivas, and G. Nadeau, "Probabilistic Seismic Stability Analysis - A Case Study", Report, No. CE-79-1, Dept. of Civ. Engr., RPI, Troy, N.Y. 12181

D. A-GRIVAS[1] and M.E. HARR[2]

1 - Rensselaer Polytechnic Institute
2 - Purdue University

The overall objective of this NSF sponsored project is to assess the reliability of earth retaining structures when subjected to a seismic environment. To achieve this objective, the following tasks have been identified and are currently pursued:

1. Description of Seismic Load

The seismic load on a retaining structure is expressed with the aid of two ground motion parameters: the maximum ground acceleration (a_{max}), and (b) the duration of the ground motion (Δ). The use of the root-mean-square (RMS) of the acceleration peaks is also explored as an alternative to the maximum ground acceleration.

2. Description of Lateral Pressures

To describe the lateral pressures acting on a retaining structure during an earthquake, the assumption is made that both the structure and the backfill material are incompressible bodies and that their rigidity is maintained during the earthquake. The magnitude, direction and points of application (distribution) of the force system in the back of the retaining structure is determined through the method of redistribution of pressure (Dubrova's method).

3. Reliability Analysis

The safety of a retaining structure is measured by its probability of failure rather than the customary factor of safety. As such a structure may fail in several modes (i.e., overturning, bearing capacity, base sliding and overall sliding) a system reliability analysis is performed.

4. Case Studies - Damage Analysis

The analysis is applied to a number of case studies involving representative sites from the Western and Northeastern regions of the United States. Moreover, in a parametric analysis of each case study, the influence is examined of significant seismic and material parameters.

In addition to testing the system, this task attempts to also assess the damage that can be had for the structure under investigation during an earthquake. Special efforts are made to relate its reliability and damage by employing a "damage factor". This is defined as a variable that ranges from zero for "no damage" to one for the complete failure of the structure under earthquake loading.

Current Status of the Present Research Project

The method of assessing the lateral earth pressures on retaining structures during earthquakes has been formulated and some preliminary results on example structures are available. The systematic pursuit of the research objectives described above was initiated in February 1980.

LEON RU-LIANG WANG

Rensselaer Polytechnic Institute

This paper reports some results obtained from a research project sponsored by the National Science Foundation under the general title 'Seismic Vulnerability, Behavior and Design of Underground Piping Systems (SVBDUPS)' carried out at Rensselaer Polytechnic Institute since September 1976. The objectives of the project are to study thoroughly the seismic response behavior of buried lifelines (such as water, sewer, oil and gas pipelines), to develop a systematic way of assessing the adequacy in terms of vulnerability to seismic damage of these systems and to propose a design criteria to seismic wave propagation effects.

Performance of Underground Pipelines in Earthquakes

The state-of-the-art of buried lifelines earthquake and its performance in earthquakes has been discussed (1,2,3). Briefly, following seismic damage/response behavior can be observed: 1. Pipeline with flexible joints experience less damage than pipelines with rigid joints; 2. Pipelines at regions of soil interface experience more damage than in regions of uniform soil; 3. Under uniform soil environment, pipelines in soft soil experience more damage than in firm soil; 4. The relative motion between the pipeline and the surrounding soil during seismic excitation is small; 5. The effects of inertia force from the pipeline itself to the response is small; 6. The axial strains in pipeline are found to be much larger than the bending strains.

With the above observations, following concluding remarks can be made: 1. The behavior of buried pipelines is governed by the relative displacements of the ground along the pipe route and not the acceleration; 2. Ductility to allow buried pipeline movement with the ground is the most important factor for the seismic design for such structures.

Influencing Parameters

The response behavior of buried pipelines to seismic wave propagation effects is influenced by the seismological, geological and geotechnical environments at the site as well as the physical parameters of the pipelines. The seismic environment determines the ground motion inputs such as maximum acceleration, velocity and displacement. The combination of geological and geotechnical effects will determine the propagation velocities required in the analysis. The local soil condition governs the resistant characteristics to pipe motions. In general, it is found that there is little experimental data in the soil resistance to longitudinal pipe motions. However, the information on soil resistance to lateral pipe motion is available (5). By a parametric approach, the frequencies of buried pipelines have been studied (4).

Quasi-Static Seismic Analysis of Buried Pipelines

Based on the observation of performance of underground pipelines in earthquakes, it would be more efficient to study the seismic response of buried pipelines to wave propagation effects in longitudinal direction by a "Quasi-Static" approach. Basically, at any instant, there will be a static equilibrium of the soil-structure interaction system in terms of ground displacements as follows:

$$[K_{system}] \{X\} = [K_{soil}] \{X_G\}$$

where $[K_{system}]$ and $[K_{soil}]$ are the symmetrical tridiagonal structural system and soil resistance matrices respectively, $\{X\}$ is the nodal axial displacement vector and $\{X_G\}$ is ground displacement vector which varies with time. Since the ground displacement varies with time, the solution of pipe strains and relative joint displacement is also a function of time. Thus, the analysis is called 'quasi-static' analysis.

To obtain conservative estimate of relative joint displacements, the response behavior of rigid segmented pipelines has been studied (7). The general formulation for actual pipeline including material parameters is given in Ref. 8. The solutions to various effects have been obtained (11). From these analyses, following conclusions can be made: 1. The most influential parameters on the response behavior of buried pipelines are the slope of the displacement-time history curve (maximum ground velocity) and seismic wave propagation velocity; 2. In general, increasing joint stiffness will increase pipe strains but reduce relative joint displacement; 3. Buried pipelines with longer pipe segment lengths, surrounded by softer soil, will produce both large pipe strains and relative joint displacement; 4. For a given joint stiffness in a pipeline, the difference in seismic response for various commonly used materials is negligible; 5. In a given geotechnical environment, larger diameter pipe produces more relative joint displacement, while smaller diameter pipe produces more pipe strains.

Failure Criteria

To aid the design of buried pipeline against earthquake, the reserved strength/strain beyond its normal stress/strain conditions is proposed as the design/failure criteria (6). In buried pipeline under combined conventional and seismic loading, bi-axial stress state is developed since conventional loads produce mainly hoop stresses whereas the seismic effect is predominantly in the longitudinal direction. To evaluate materials (such as cast iron, concrete, etc.), which have different tensile and compressive strengths, a modified Von Mises failure criteria is proposed. With these criteria and above outlined analyses procedures, a case study was conducted for Latham Water District (in Albany, New York) (9). The vulnerable zone can be identified.

Design Methodology

At the present time, there is no code or specification in U.S. to govern the design of buried pipelines to resist earthquakes. Engineers in seismic prone areas have used passive design practices to reduce seismic damage and minimize hazardous effects. The passive design considerations include: 1. to provide redundancy and blow-off values to the system and, 2. to use available flexible joints and ductile material when possible.

To facilitate the development of future design code, the research at Rensselaer has attempted to outline a design methodology (10, 11, 12). Briefly, it involves: 1. site environment evaluations, 2. engineering decision making, and 3. design analyses.

Future Research

The discussions above have centered on single continuous or segmented pipelines on uniform (simple) environments. Further research tasks in progress at RPI are as follows: 1. Study of simple piping systems with varying soil conditions; 2. Study of simple piping systems with varying geological environments, and 3. Response analyses of general piping systems including non-linear resistant characteristics.

References

1. Leon R.L. Wang and Michael J. O'Rourke, "State-of-the-Art of Buried Lifeline Earthquake Engineering", Proc. of Current State Knowledge of Lifeline Earthquake Engineering, ASCE/Los Angeles, CA, August 30-31, 1977, pp. 252-266.
2. Leon R.L. Wang, "Performance of Underground Pipelines in Earthquakes", Proc. on the Specialty Conference on Earthquake Engineering and Soil Dynamics, ASCE/Pasadena, CA, June 19-21, 1978, Vol. III, pp. 1344-1346.
3. Leon R.L. Wang and Michael J. O'Rourke, "Overview of Buried Pipelines Under Seismic Loading", Journal of the Technical Councils of ASCE, Vol. 104, No. TC1, Nov. 1978, pp. 121-130.
4. Leon R.L. Wang, "Vibration Frequencies of Buried Pipelines", Journal of the Technical Councils of ASCE, Vol. 104, No. TC1, Nov. 1978,pp.71-89.
5. Leon R.L. Wang, "Discussion on Soil Restraint Against Horizontal Motion of Pipes", Journal of Geotechnical Engineering Division of ASCE, Vol. 104, No. GT12, Dec. 1978, pp. 1532-1536.
6. Leon R.L. Wang and Raymond C.Y. Fung, "Seismic Design Criteria for Buried Pipelines", Proc. of Pipeline Division Specialty Conference, ASCE/New Orleans, La, January 15-17, 1979, pp. 130-145.
7. Leon R.L. Wang and K.M. Cheng, "Seismic Response Behavior of Buried Pipelines", Journal of Pressure Vessel Technology, ASME, Vol. 101, No. 1, Feb. 1979, pp. 21-30.
8. Leon R.L. Wang and Eric Fok, "Quasi-static Seismic Analysis of Buried Pipelines", Proc. 7th Canadian Congress of Applied Mechanics, Sherbrook, Canada, May 28-June 1, 1979, Vol. 1, pp. 461-462.
9. Richard R. Pikul, Leon R.L. Wang and Michael J. O'Rourke, "Seismic Vulnerability of Water Distribution Systems-A Case Study", Proc. 3rd Canadian Conference on Earthquake Engineering, Montreal, Canada, June 4-6, 1979, pp. 1365-1388.
10. Leon R.L. Wang and Holly A. Cornell, "Effect of Earthquake on Buried Pipelines", Proc. AWWA Annual Conference and Exposition, San Francisco, CA, June 24-29, 1979, pp. 361-373.
11. Leon R.L. Wang, "Some Aspects of Seismic Resistant Design of Buried Pipelines", Proc. of Lifeline Earthquake Engineering - Buried Pipelines, Seismic Risk and Instrumentation, ASME 3rd National Congress on Pressure Vessels and Piping, PVP-34, June 25-29, 1979, pp. 117-131.
12. Leon R.L. Wang, "Seismic Analysis and Design of Buried Pipelines", Proc. of International Conference on Engineering Protection from Natural Disasters, Bangkok, Thailand, January 7-9, 1980, pp. 71-83.

Y. S. CHAE, W. C. AU and Y. C. CHIANG

Department of Civil and Environmental Engineering
Rutgers University

This paper summarizes one phase of current research at Rutgers University in the area of dynamic properties and behavior of soils. Parametric effects on dynamic properties of soils, and prediction of the dynamic properties of soils from the results of static tests have been the subjects for research in recent years. This paper summarizes the results of the latter.

Introduction

Determination of the dynamic shear modulus of soils is of fundamental importance in the analysis of dynamically loaded foundations, earthquake-induced ground motions and soil-structure interaction as analytical techniques now available require the input of well-defined dynamic properties of soils. There are many test parameters which affect the dynamic properties however, and evaluation of the test parameters required to describe the dynamic behavior of soils involves sophisticated laboratory dynamic tests such as resonant column or cyclic shear tests. The ability to predict the dynamic properties from conventional simple static tests, which are routinely done, would therefore be beneficial and advantageous in many situations especially for use in preliminary analysis.

Experimental Program

The materials used for the study were a uniform sand, a non-active fine silty clay and a highly-active bentonite clay. The sand particles ranged from 2 to 0.074 mm in diameter with a uniformity coefficient of 3.43. The silty clay had a liquid limit of 30.1% and plasticity index of 9.8%. The bentonite clay was much finer in grain size than the silty clay and had a liquid limit of 593% and the plasticity index of 544%. In order to increase the range for static and dynamic shear strength of the soils, the sand and silty clay specimens were treated either with cement, lime or a lime and fly-ash combination. The bentonite clay was treated either with lime, salt or a lime-salt combination.

The dynamic shear modulus was determined by means of the resonant column technique in torsion on remolded specimens prepared by a miniature compactor designed specially for this study. A detailed discussion of the test apparatus, test procedure and the theoretical concept of torsional resonant column technique used in this study may be found [1]. Immediately following a dynamic test, the specimen was tested in a static triaxial compression apparatus to evaluate the static properties of the soil for the purpose of correlating with dynamic properties.

The major independent test parameters considered were moisture content and treatment level of additives for the soils, and confining pressure and shear strain amplitude for the testing apparatus. The specimens were tested at confining pressures ranging up to 35 psi. At a given confining pressure, the dynamic shear modulus was determined at five different shear strain levels ranging up to 2.80 x 10^{-4}. Moisture content was varied over a wide range on both sides of the optimum. Treatment levels were varied over a wide range.

Analysis and Discussion of Test Results

Evaluation of the effect of such test parameters as confining pressure, strain amplitude, moisture content, soil structure, type of additives and treatment level has been reported [1, 2, 3]. The typical rest results and essential findings are summarized herein.

In all of the tests conducted, a striking similarity in pattern was noted between the gain of static strength and the gain of dynamic shear modulus with increasing level of treatment, and therefore, a correlation between the two could be derived. Fig. 1 is a plot of the maximum dynamic shear modulus against the static strength of all specimens tested. It is apparent from the figure that a linear relationship exists between the static strength and the dynamic shear modulus, except for those soil specimens having very low strength, regardless of the type of additives, treatment level and moisture content. Using linear regression analysis, the following empirical equations for predicting the maximum dynamic shear modulus, G in ksi, from the static strength, $\bar{\sigma}_d$ in ksi, were obtained for the different soils:

For sand $\quad G = 420\ \bar{\sigma}_d + 14$

For silty clay $\quad G = 600\ \bar{\sigma}_d + 8$

For bentonite clay $\quad G = 130\ \bar{\sigma}_d + 14$

It is observed that the relationship between the maximum dynamic shear modulus and static strength is independent of test parameters, and is a function only of the type of soil. Thus, the maximum dynamic shear modulus of any soil may be obtained from the static strength based on a simple relationship:

$$G = m\ \bar{\sigma}_d + n$$

where m and n are the constants for a given type of soil.

References

1. Au, W. C. and Chae, Y. S., "Dynamic Shear Modulus of Treated Expansive Soils," J. Geotech Eng. Div. ASCE, Vol. 106, March, 1980, pp. 255-273.

2. Chae, Y. S. and Chiang, Y. C., "Dynamic Properties of Lime and LFA Treated Soils," Proc. Speciality Conference on Earthquake Engineering and Soil Dynamics, ASCE, Vol. 1, 1978, pp. 308-324.

3. Chiang, Y. C. and Chae, Y. S., "Dynamic Properties of Cement Treated Soils," Highway Research Record 379, 1972, pp. 39-51.

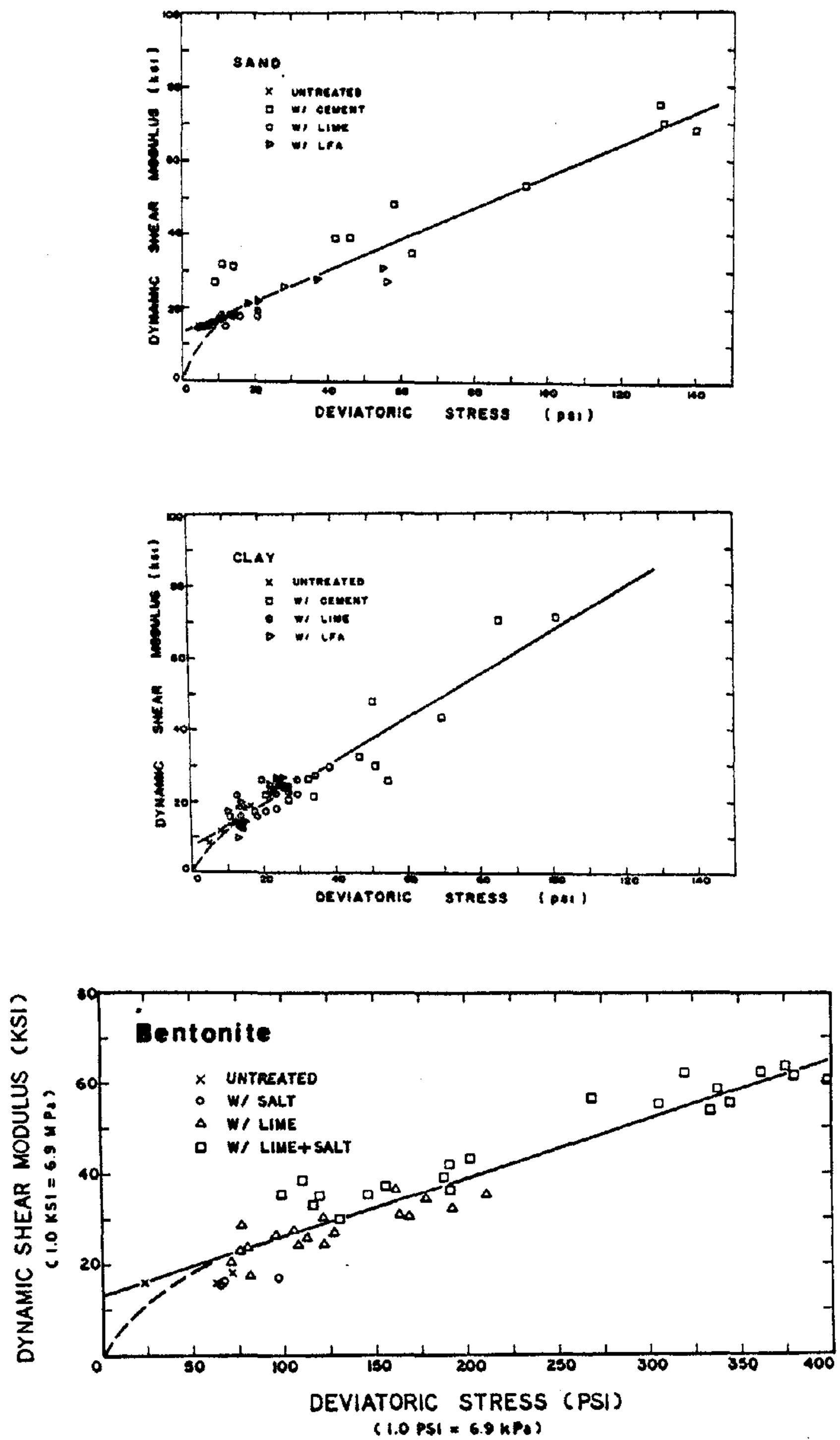


FIG. 1 .—Correlation between Dynamic Shear Modulus and Static Strength

Jose M. Roesset

The University of Texas at Austin

This paper summarizes current research at the University of Texas at Austin. Due to lack of sponsored research since the author left M.I.T. and moved to Texas most of the work has been conducted as a series of small unsponsored projects. Initial studies on the dynamic response of piles are being conducted under a small grant from Union Oil Company and additional funds from the Bureau of Engineering Research of the University. Additional studies are being initiated in expectation of receiving a grant from the National Science Foundation.

Accuracy of Nonlinear Analyses

Analyses of wave propagation in soil deposits are normally conducted using an iterative equivalent linearization procedure originally suggested by Seed and Idness. Comparative studies carried out by Constantopoulos had indicated that this procudure tended to overestimate in general peak accelerations at the free surface of the soil deposit by up to 20% while underestimating more severely strains and displacements. Further studies conducted more recently by D'Appolonia indicate that in the case of soft soil deposits and large excitations accelerations may be badly underestimated by the equivalent linearization as opposed to a nonlinear analysis performed with the program CHARSOIL. On the other hand similar comparisons by Dames and Moore suggest that for these cases accelerations may be grossly overestimated by a conclusion which is basically the opposite.

These studies indicate that the validity of the iterative linear solution needs further investigation, particularly for extreme cases, but they also suggest that the accuracy of true nonlinear analysis may require some evaluation. Two factors which may significantly affect the response, particularly in the high frequency range, are the way in thich sharp changes in stifness are handled (related to the time step of integration) and the characteristics of the nonlinear model (whether the model has or not complete memory). It appears that some of the models used in practice do not keep track of all reversal points. A series of parametric studies using different integration procedures and different idealizations of the nonlinear soil model are being conducted to assess better the importance of these two factors.

Nonlinear Modal Analysis

A series of studies were conducted to evaluate the possibility of using modal analysis, with the elastic modes as generalized coordinates, to predict the dynamic response of nonlinear systems. The advantage of this procedure is that explicit integration schemes can still be used for each mode, the time step of integration being controlled by the number of models used. Values of modal damping can be défined directly for each mode without the need to compute an artificial damping matrix. Finally inspection of the natural modes and their contribution to the total response provides a valuable insight into the structure's behavior.

When all the modes are used the exact solution is obtained within the limitations imposed by the accuracy of the numerical integration procedure (i.e., a solution comparable to that which would be obtained using direct integration of the equations of motion). The results indicate, however, that three to five modes are generally sufficient to reproduce key features of the solution within a desirable accuracy.

Dynamic Stiffness of Piles

A comprehehsive investigation of the dynamic stiffness of piles and pile foundations is being planned by the author in combination with Professors Kenneth Stokoe and Steven Wright. The research contemplates analytical and experimental studies on single piles and pile groups subjected to dynamic excitation of small amplitude but arbitrary frequency and on single piles under cyclic load with large amplitude.

In preparation for this work, and as a preliminary step, a concrete pile with 6 inch diameter and 5 foot length has been placed in a test pit constructed in the ground and filled with sand whose properties are well known. The pit has a diameter of 25 ft. and a depth of 12 ft. The properties of the sand are relatively similar to those of the surrounding ground in order to minimize reflections at the interface although this discontinuity will also be modelled analytically. The pile has an inner core composed of a reinforcing cage housing four vertical velocity transducers spaced along the pile length. A metal plate is embedded in the top of the inner core and serves as attachment of the vibrator to the pile. An electro-magnetic vibrator is used to excite the pile vertically. The pile stiffness will be determined from measurements of amplitude and phases of the motions at the pile head and will be compared to analytical predictions using various formulations. In addition measurements will be made along the pile length and at various points within the sand mass.

Additional Work

In addition to the work described above an analytical study of the dynamic behavior and response of concrete members subjected to biaxial excitation has been initiated in conjunction with Professor Jirsa and as a complememt to his experimental research program. It is intended to investigate the ability of various models to reproduce best results for biaxial excitation as well as for the case when shear failure controls.

G. AYALA-MILIAN

Virginia Polytechnic Institute and State University
and National Autonomous University of Mexico

This report summarizes three research projects initiated at the Institute of Engineering with the collaboration of M. Romo and is currently in progress in Mexico and at VPI & SU where the author is a visiting professor in the Department of Civil Engineering.

Dynamic Response and Deformation Analysis of Two Mexican Dams: The behaviour of dams and embankments subjected to earthquake loading has been the subject of research at the Institute of Engineering of the National Autonomous University of Mexico since the early sixties. Till recently, the comparison of analytical results with observed behaviour had not been attempted. However, after the occurrence of the March 14 Petatlan Earthquake investigations in this topic have been done. Due to the availability of recorded motions and permanent deformations Fl Infiernillo and La Villita Dam were chosen. For both dams the initial stresses were computed using a static finite element procedure that simulated the construction sequences.

Since the dynamic characteristics of the embankment materials were not known, these characteristics were initially estimated and modified there for numerical simulations to obtain earthquake responses that matched observed behaviour. The adequacy of the determined dynamic properties has been assessed by reanalyzing both dams under subsequent recorded motions. Though the agreement between the recorded and calculated motions is satisfactory further research is in progress to account for three dimensional effects approximately by using Fourier series expansions in the third dimension. For the estimation of permanent deformations induced by earthquake loading simplified procedures are being evaluated. This methods under study are Newmark's, Makdisi-Seed's and Resendiz-Romo's. Estimated and observed freeboard losses have been compared for the two above mentioned dams. This comparison has shown that Newmark's and Makdisi-Seed's method give inaccurate and unsafe results, whereas the procedure suggested by Resendiz and Romo gives acceptable results on the safe side.

For the validation of this method an extensive experimental programme is being carried out by J. L. Leon in the Institute of Engineering. At VPI & SU the author is carrying out a detailed survey of reported cases histories as well as true nonlinear finite element dynamic analyses to validate the reismic coefficient distribution obtained by simplified methods.

Earthquake Performance of Underground Water Pipelines: During the March 14 earthquake one of the main underground water supplies to Mexico City was heavily damaged. The pipeline was an assemblage of 72 inch diameter gasket-jointed concrete pipes with joints of the type flush bell. The damage occurred in seven points and consisted of compression failures at the joints. Preliminary statigraphic information of the sites shows correlation of the damage with local topographic conditions. In six of the cases, the failures occurred in transition zones with the pipeline located in the dipping layer. The remaining failure occurred at the centre of an alluvial valley with no apparent site effects.

On the basis of the above field information the effect of the local soil conditions on the earthquake damage of gasket-jointed concrete pipelines is under investigation. In the absence of instrumental records, earthquake motions at transition zones are being determined by using a finite element programme previously developed by the author. Frequently domain solutions show emplifications of up to ten times the incident motion. Ti-me domain solutions will be obtained using Fourier analysis. Once the free field conditions are finally determined the interaction effects will be evaluated by using a simplified interaction model which ignores relative displacements between the pipeline and the surrounding soil.

Improved Accuracy in Dynamic Finite Element Analyses: This research has been focused in two different aspects of finite element approximation. The first deals with the definition of element mass matrix as a linear combination of the lumped and consistent mass matrices as it was previously suggested by Lysmer and his co-workers. Preliminary theoretical results show that the optimum value of the parameter which defines such a combination is strongly dependent on the type of wave and the number of elements per wave length. Currently the study has been completed for body waves and research is in progress for surface waves. The final outcome of this research will be the definition of optimum combinations of mass matrices for different wave conditions.

The second aspect involved the derivation of element stiffness matrices using a boundary integral formulation. The advantage of this formulation is that, with relative simplicity, the accuracy of stresses within the element will be improved. This research is of relevance in true nonlinear dynamic analyses where the accuracy in the stresses is of relevance.

O. M. EL-SHAFEE AND P. L. GOULD

Washington University

Seismic Response of Cooling Towers on Shallow Foundations

An analytical method has been developed to determine the seismic response of axisymmetric shells and shell-like structures supported over shallow foundations in the form of ring footing. The soil-structure interaction effects are included through the development of a boundary system at the contact area between the footing and the soil medium. The method has been applied for cooling towers supported by ring footing underlied by a variety of soil conditions.

System Modeling

High-precision rotational shell finite elements (1) have been used to model the axisymmetric shell. The soil medium has been modeled using axisymmetrical isoparametric quadratic solid elements with transmitting vertical boundaries, placed directly at the edge of the structure. The lower boundary is assumed to be fixed at some depth from the foundation level. The total dynamic stiffness matrix of the soil is the sum of the dynamic stiffness matrix of the core and the boundary matrix resulting from the solution of a free wave propagation problem in the far field with the requirement of preserving the equilibrium at the vertical transmitting boundaries (2).

The impedence matrix is obtained by inverting the flexibility matrix resulting from the solution for a harmonic force $e^{i\omega t}$ applied at the common d.o.f between the structure and the soil, individually in each of the degrees of freedom.

The connection problem between the three dimensional soil medium and the two dimensional structure element is established by introducing a frequency dependent dynamic boundary system at the common degrees of freedom between the ring footing and the underlaying soil. The soil stiffnesses and damping at the connecting nodal point are formulated from the impedence matrix.

Analysis

The interaction effect on the dynamic properties of the shell has been studied through a free vibration analysis of a cooling tower founded on compliant soil. The analysis is carried out at the fundamental frequency of the tower on rigid foundations.

To examine the soil effect on the seismic response of the cooling tower, a response spectrum and a time history analysis are conducted for the proposed model. The ground motion is introduced at the foundation level directly since the substructure method used for the dynamic analysis requires no deconvolution, which is in essentially an inertial coupling method.

References

1) Sen, S., Gould, P. and Suryoutomo, H., "High-Precision Static and Dynamic Finite Element Analysis of Shells of Revolution with Application to Hyperboloidal Shells on Discrete Supports", Research Report No. 23, Structural Division, Washington University, St. Louis, Mo., Nov. 1973.

2) El-Shafee, O., and Gould, P., "Analytical Method for Determining Seismic Response of Cooling Towers on Footing Foundations", Research Report No. 55, Structural Division, Washington University, St. Louis, Mo., Sept. 1979.

M. NOVAK

The University of Western Ontario

This paper presents a summary of research conducted at the University of Western Ontario into behaviour of buried pipelines in seismic environment. The study is theoretical, confined to straight pipes and deals with the following cases: deterministic response to travelling waves acting under arbitrary angle of incidence in homogeneous medium and in two different media separated by a vertical boundary; stochastic response to ground motion which is random in time and space; and reduction of pipe stresses due to pipe insulation or slippage between the soil and the pipe. The research is sponsored by the National Science and Engineering Research Council.

Response to travelling waves. The response to travelling waves is analyzed using a lumped mass model with soil reactions derived by means of the continuum theory. This theory indicates that buried pipes are heavily damped. The magnitude of damping can be evaluated for any vibration modes. The stresses in the pipe are reduced by soil structure interaction but this reduction is usually quite small. In pipes crossing an interface between two different media, a sharp increase in stresses occurs in the vicinity of the interface.

Response to random excitation. In the analyses of response to random ground motion a distributed mass system is used to model the pipe. The ground motion is assumed to be partially correlated in space and time. This type of motion is described using cross-spectra expressed in terms of a dimensionless frequency $f|y_2-y_1|/V$ in which f = frequency in Hz, $|y_2-y_1|$ = separation of two stations and V = wave velocity. Such a cross-spectrum accounts for the decay of correlation with both frequency and separation. (Fig. 1)

The results of the analysis indicate that the partially correlated ground motion may produce stresses well in excess of those calculated under the usual assumption of a fully correlated ground motion. More information on spatial correlation of ground motion is, therefore, needed. The same approach could be used for tunnels, dams and bridges.

Pipe insulation and slippage. The effects of pipe insulation and slippage between the pipe and soil are investigated using the same models as in the above cases except for the soil reactions to the pipe motion that are derived from a composite medium. This medium consists of a soft layer (ring) around the pipe and an outer homogeneous medium extending to infinity. The pipe stresses appear to be reduced by both insulation and slippage but the reduction is not as great as might be expected. (Fig. 2)

References

Novak, M. and Hindy, A., "Seismic Response of Buried Pipelines," 3rd Canadian Conf. on Earthquake Engineering, Montreal, June, 1979.

Hindy, A. and Novak, M. "Pipeline Response to Random Ground Motion," Journal of Engineering Mechanics Division, ASCE (to appear).

Hindy, A. and Novak, M. "Earthquake Response to Buried Insulated Pipes," Journal of Engineering Mechanics Division, ASCE (to appear).

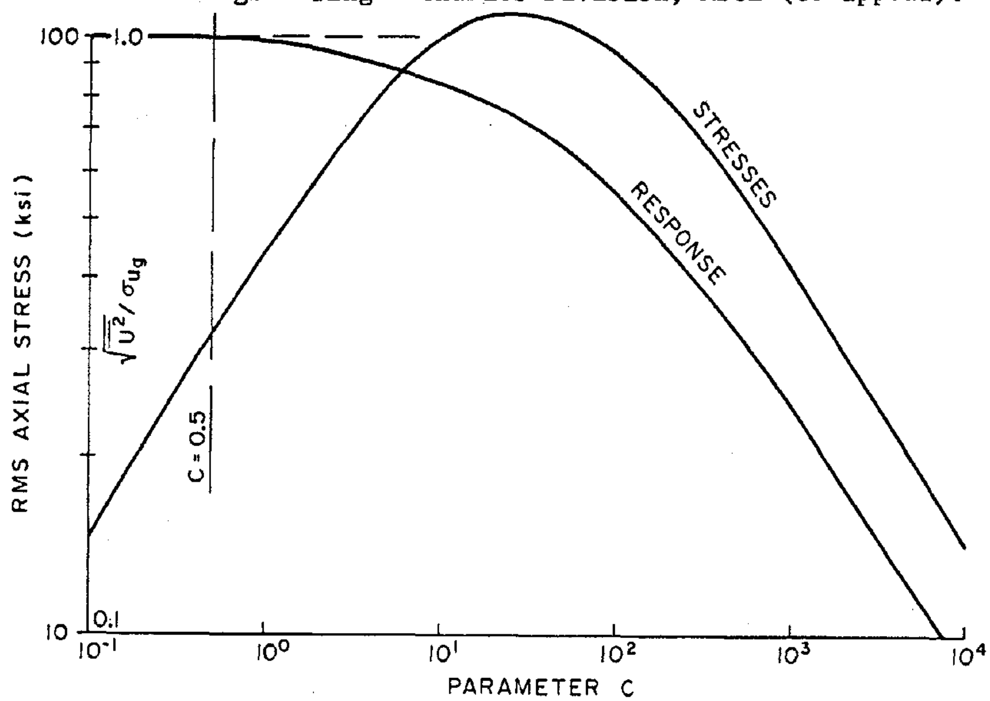


Figure 1 Variation of Pipe Response and Stresses With Intensity of Correlation (Parameter c)

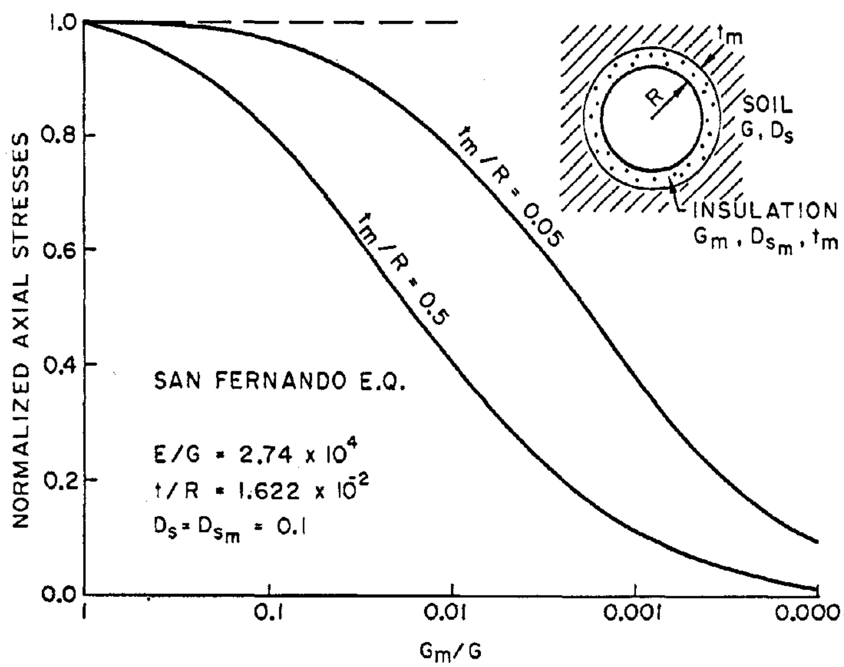


Figure 2 Effect of Pipe Insulation On the Peak Axial Stresses (Input Is A Fully Correlated Travelling Wave)

SEISMIC RISK, SEISMIC DESIGN & CODES

ROLAND L. SHARPE

Applied Technology Council

This paper summarizes the efforts of the Applied Technology Council over the past three years on two projects involving development of seismic design guidelines.

Project ATC-5 - Single Family Masonry Dwellings in Seismic Zone 2

ATC-5 requires a close working relationship between researchers at the University of California at Berkeley and an Advisory Panel assembled by ATC. UCB under contract with HUD has conducted shaking table tests of four house models and various cyclic tests of connection details. The research testing has been performed in close cooperation with the ATC Advisory Panel which is composed of the ATC Project Manager, three practicing engineers, a home builder and HUD-FHA representatives.

The Advisory Panel including the author initially met with UCB representatives, thoroughly reviewed the basic requirements for the research and the end results expected, and how the various tests should be set up to get maximum information, which then hopefully could be directly applied to the design guidelines. There has been a good spirit of cooperation among all parties involved. UCB developed the initial experimental design after consultation with the Advisory Panel. The Advisory Panel then reviewed the program in detail and made numerous recommendations. After discussion most of the suggestions were accepted. A number of connection tests were developed, based largely on Advisory Panel suggestions and recommendations. The researchers developed the test samples, determined how many tests should be run and how the loads should be applied. Nearly concurrently, shaking table tests were run on the first house model. The Advisory Panel witnessed some of the tests. After the results of the tests were reduced and evaluated, they were discussed in a joint meeting and the second shaking table test planned. This process continued through four different shaking table tests. Each test was designed with full cooperation between the Advisory Panel and the UCB researchers.

There was considerable discussion on the effects of scale, workmanship, size of house, deflection of the roof diaphragm, foundation compliance, moisture conditions during construction, and many other factors. However, it is the author's opinion that the results produced from these tests, when fully evaluated by the Advisory Panel and the researchers, will provide meaningful input for seismic design guidelines. An ATC subcontractor has drafted guidelines based on the research results; they are still under review. The process has demonstrated a straight forward procedure for ensuring that research results are directly transformable to practice.

Project ATC-6 - Highway Bridges in the U.S.

ATC-6 is funded by the Federal Highway Administration and has involved the combined efforts of a fifteen member Engineering Panel composed of three researchers, four design professionals, four AASHTO members, two FHWA representatives and two ATC staff. The objective was to combine the knowledge and experience of researchers with the needs of professional practitioners and state highway bridge engineers. The project was initiated about three years ago with a detailed review of highway bridge seismic research results and of earthquake damage to bridges. A seminar-workshop was sponsored by NSF in January 1979 with 23 researchers, practitioners and bridge officials from the U.S., Japan, New Zealand and Portugal presenting papers. Some 25 other participants attended and helped develop future research needs. The workshop also provided valuable insight towards development of the seismic design guidelines.

Recently the draft guidelines were used to redesign about 25 bridges from throughout the U.S. The redesigns were presented at a three-day workshop; the results have indicated the need for numerous detail changes in the guidelines although there was general concurrence with the overall philosophy of the requirements. The guidelines will be redrafted, reviewed by the Engineering Panel and design examples prepared. The FHWA intends then to submit the guidelines to the American Association of State Highway and Transportation Officials (AASHTO) for consideration and potential adoption.

This project has demonstrated another method for bringing together researchers, practitioners, and owner representatives to transform research and theory into practice.

ATC as a matter of policy retains qualified researchers, consultants, firms and others who have the specialized expertise necessary to perform a given project. ATC does not attempt to build up a staff of experts. ATC's basic goals are to transform research results into practice and to foster research where needed to enhance the public safety.

M. SHINOZUKA, R. TAN and T. KOIKE

Department of Civil Engineering and Engineering Mechanics
Columbia University New York, N.Y. 10027

INTRODUCTION

In a recent paper [1], the senior author presented a seismic risk analysis procedure for underground water transmission network systems under the conditions of fault movements where, as the first step towards developing a realistic and practical risk analysis procedure, the state of connectivity of the network was used as a measure of the system's performance. The connectivity is defined as the capability of the network to transmit water from at least one of the supply stations to the demand nodes in the system. However, the connectivity thus defined does not necessarily reflect the functional serviceability of the system. For example, even when a transmission path remains open between one of the supply stations and one of the nodes following an earthquake, the water pressure and flow rate at that node may drop, due to possible earthquake damage, below the level required for effective post-earthquake firefighting. Hence, if the capability of effective firefighting is the criterion for system serviceability, the system can be deemed unserviceable even while its connectivity still remains intact.

A study is currently under way to assess the magnitude of seismic risk in terms of the degree of possible unserviceability resulting from destructive earthquakes. In the study, it is postulated that a water transmission system is serviceable when its firefighting capabilities (measured in terms of water pressure and flow rate at specified nodes) remain intact immediately following an earthquake. With the aid of the results obtained in Ref. 1, for the failure probabilities of individual links in the network, Monte Carlo techniques are used to generate samples of simulated states of damage for water transmission networks. The Newton-Raphson method is then utilized to analyze each of these damaged networks for its flow characteristics and, at the same time, to determine whether or not it still remains serviceable. The probability of system serviceability is estimated as the ratio of the number of simulated networks that are found serviceable to the total number of networks simulated. A water transmission network system similar to that of the City of Los Angeles is used to demonstrate the numerical results.

SERVICEABILITY CRITERIA

Three possible states of serviceability are defined at each demand node. A state of major unserviceability corresponds to the condition that at least either the water pressure or the flow rate is less than the respective minimum requirements (E_{min} for pressure and F_{min} for flow rate) for firefighting. A state of moderate unserviceability represents the condition under which both the pressure and the flow rate satisfy the minimum requirements but neither of them exceeds the minimum allowable amount associated with the undamaged original network (E_m for pressure and F_m for flow rate). A state of minor unserviceability is then defined as that in which the pressure and the flow rate exceed E_m and F_m, respectively, and therefore minor unserviceability implies a state of (normal) serviceability. Fig. 1 shows these serviceability criteria schematically.

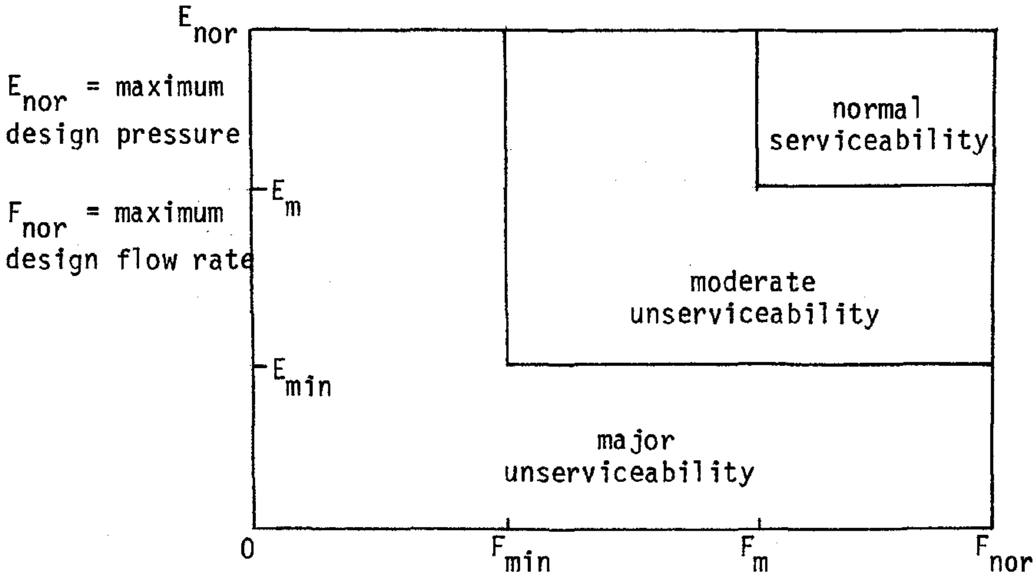


Fig. 1 Serviceability Criteria

Monte Carlo Simulation

With the aid of Monte Carlo techniques, the present study generates samples of simulated states of the physical damage of the network. For this purpose, the (conditional) probabilities $P\{L_{if} \mid m,\ell\}$, $P\{L_{im} \mid m,\ell\}$ and $P\{L_{is} \mid m,\ell\}$ evaluated in Ref. 1 are used, where $P\{L_{if} \mid m,\ell\}$ denote the (conditional) probability of the i-th link (branch) of the network in a state of major physical damage (e.g., complete pipe rupture), $P\{L_{im} \mid m,\ell\}$ in a state of moderate damage (partial rupture and/or considerable leakage) and $P\{L_{is} \mid m,\ell\}$ in a state of minor damage (little damage or leakage). These probabilities are conditional to the magnitude m of the earthquake and the epicentral location ℓ.

The Newton-Raphson method is then applied to each of these networks with simulated states of physical damage to examine whether it is in a state of major, moderate or minor unserviceability. The number of networks found to be in a state of major unserviceability divided by the total number of networks used in the simulation produces an estimate for the probability of major unserviceability. Similarly, the probabilities of moderate and minor unserviceability are estimated. In this analysis, however, appropriate assumptions are used with respect to the relationship between the physical damages sustained by the links and nodes and the conditions of water leakage through and pressure at these branches and nodes.

Dealing with a water transmission network system adapted from that of Los Angeles, penetrated and surrounded by a number of major faults, numerical examples are worked out for various values of m and ℓ so that eventually the absolute (rather than the conditional) probabilities of major, moderate and minor unserviceability can be estimated.

ACKNOWLEDGEMENTS

This work is supported by the National Science Foundation under grant No. NSF-PFR-78-15049 with Dr. S.C. Liu as Program Manager.

REFERENCES

1. Shinozuka, M. and Koike, T., "Seismic Risk of Underground Lifeline Systems Resulting from Fault Movement," Proceedings of the 2nd U.S. National Conference on Earthquake Engineering, Stanford University, Stanford, California, August 22-24, 1979, pp. 663-672.

ACHINTYA HALDAR

Georgia Institute of Technology

This paper summarizes current research at Georgia Institute of Technology which will be sponsored by the National Science Foundation in the area of probabilistic assessment of damage in earthquake-induced liquefaction. An attempt will be made here to develop a probabilistic model which will estimate the damage associated with liquefaction. This will require going one step beyond the evaluation of liquefaction potential.

The damage associated with earthquake-induced liquefaction needs better understanding, since liquefaction can result in damage to property and the environment and suffering and loss of human life. The devastating damage due to soil liquefaction in Anchorage, Alaska and Niigata, Japan in 1964 is a very recent reminder of the critical nature of such events. Soil liquefaction following earthquakes in these areas resulted in landslides, subsidence of foundations, formation of sand volcanoes, damage to earth structures, lateral movement of structures resting on soil, disruption of services, and loss of human life.

Limiting or eliminating damage during liquefaction will be a reasonable criterion in studying this problem. Since a volume of sand has to undergo a considerable amount of strain to produce a noticeable amount of damage at the referenced location, the soil properties affecting liquefaction potential in the liquifiable volume have to be modeled in three dimensions. Long-distance fluctuations and local variations in soil properties can only be modeled effectively using probability theory. Seismic loading is also unpredictable. This necessitates the availability of a simple but efficient and practical probabilistic model to study the risk of damage associated with the liquefaction phenomenon.

Earthquake-induced liquefaction is a very complex problem, and several methods with various degrees of complexity (both deterministic and probabilistic) are available to help solve the problem [1,2,3,4,5,6,8]. However, the damage aspect of the problem has not received proper attention so far. Liquefaction does not always cause damage.

Estimation of the minimum volume of sand at a particular depth, which may cause damage at the referenced location if it liquefies, is very important information as far as the damage associated with liquefaction is concerned. Information on this subject will be obtained directly from the case histories reported in the literature, or indirectly from the information on differential settlement or similar studies.

Liquefaction of a sufficient volume of sand is our major concern. Sand deposits under the water table are not always homogeneous. Soil deposits typically exhibit local variations about their average properties or about major trends (horizontally and vertically). Average properties or long distance fluctuations can be modeled by deterministic models, but estimating local variations in a soil deposit is not practical with a deterministic model. A probabilistic model of the profile provides adequate characterization in terms of a few additional parameters. In this study, some of the important factors that affect liquefaction potential, such as relative density, mean grain size, initial confining pressure, intensity of ground shaking, duration of ground shaking, etc. will be identified. Some other recently identified factors, whose influence on liquefaction potential evaluation may be significant when laboratory methods are used, will be considered. They are methods of preparation of test specimens, size of specimens, sample disturbances, effect of system compliance, soil fabric (grain and interparticle contact orientations), period under sustained load, i.e., the age of the deposit, previous strain history of the deposit, overconsolidation, multidirectional shaking, etc. Sufficient information is now available on these factors and will be used in this study for statistical analysis.

Using all the aforementioned information, a probabilistic model will be developed considering the three-dimensional probabilistic characteristics of nonhomogeneity of all soil properties that can be identified with the liquefaction problem and the random nature of the earthquake loading. The methodology will be verified using available case studies. Attempts will also be made to identify the minimum amount of site exploration required to obtain data to model soil properties probabilistically in three dimensions. Required information on minimum numbers or spacings of boreholes are expected to be obtained from this study.

Estimation of liquefaction risk is very important information but does not always show the damage potential. Seed wrote (7), "It is apparent that if the stress ratio causing 5% strain at a relative density of 54% is even slightly exceeded, then the sand will undergo strains up to ±30% with almost certain catastrophic consequences. However, if the stress ratio causing 5% strain at a relative density of 82% is slightly exceeded, the only result would be to cause a strain of perhaps 6% even if the factor of safety should drop to a value of 0.5." This type of information can be used to estimate the damage probability. Annual as well as risk of damage in t years can be obtained from the above information.

The model will be developed in such a way that it can be updated in the future as more information becomes available on the subject. Provision will also be made for the incorporation of experience or judgmental information. With the help of a computer program written for this purpose, many ideal soil profiles will be studied. A required soil parameter may be constant or may be varying in the deposit in any given manner, e.g., linearly, parabolicly, sinusoidally, or any other way, even very erratically. This type of study will give a better understanding of the problem and help to develop tables or charts for practical use.

The objective of this research is to develop a simple but efficient and practical probabilistic model. It could be used as a design aid by practicing engineers. This will also provide a better understanding of the liquefaction problem and verify some of the assumptions made in the complicated methods currently available. It will also identify some siting criteria for important structures. Voluminous information available in the literature will be used to develop this model.

REFERENCES

1. Castro, G., "Liquefaction and Cyclic Mobility of Saturated Sands," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT6, Proc. Paper 11388, June 1975, pp. 551-569.

2. Christian, J. T. and Swiger, W. F., "Statistics of Liquefaction and SPT Results," Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT11, Proc. Paper 11701, Nov. 1975, pp. 1135-1150.

3. Donovan, N. C., "A Stochastic Approach to the Seismic Liquefaction Problem," Proceedings, Conference on Statistics and Probability in Soil and Structural Engineering, Hong Kong, Sept. 1971, pp. 513-535.

4. Faccioli. E., "A Stochastic Model for Predicting Seismic Failure in a Soil Deposit," Earthquake Engineering and Structural Dynamics, Vol. 1, 1973, pp. 293-307.

5. Fardis, M. N. and Veneziano, D., "Probabilistic Liquefaction of Sands During Earthquakes," Report No. R79-14, Massachusetts Institute of Technology, Cambridge, Mass., March 1979.

6. Haldar, A. and Tang, W. H., "Probabilistic Evaluation of Liquefaction Potential," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, Proc. Paper 14374, Feb. 1979, pp. 145-163.

7. Seed, H. B., "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground During Earthquakes," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, Proc. Paper 14380, Feb. 1979, pp. 201-255.

8. Seed, H. B. and Idriss, I. M., "Simplified Procedure for Evaluating Soil Liquefaction Potential," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 97, No. SM9, Proc. Paper 8371, Sept. 1971, pp. 1249-1273.

A. H-S. ANG

University of Illionis at Urbana-Champaign

The studies reported herein are conducted as part of a program on the safety evaluation of structures to earthquakes and other natural hazards, supported by the National Science Foundation Division of Problem-Focused Research under Grant No. ENV-77-09090.

The overall objective of the program is the development of an effective methodology for evaluating the safety of structures to earthquakes and other natural hazards, and to implement this methodology in the safety assessment of major classes of structures and formulation of associated probabilistic bases for design. A realistic assessment of structural safety, or the assurance of safety in design, against the extreme forces of natural hazards may be based on a measure of risk in terms of probability, specifically the probability of damage or failure. Accordingly, the several components of the study program are all aimed at developing a practical method for evaluating the safety of structures against various levels of damage or failure (including collapse) when subjected to the lifetime maximum load. The program is now in its second year of the Phase I two-year study. Much of the research during this first phase is devoted to the development of the necessary analytical tools and demonstrating the applications for limited classes of structures. The work accomplished thus far, as well as those in progress, in the various components of the program may be summarized as follows.

Analysis of Seismic and Other Extreme Hazards

In evaluating the safety of a structure, it is the maximum load that can be expected over the life of the structure that is of principal concern. The occurrence of earthquakes in time as well as in space is, of course, unpredictable; moreover, the magnitude of an earthquake and therefore also the intensity at a given site may be described with a random variable. The lifetime maximum seismic loading that can be expected at a given site, therefore, may be determined only in terms of probability. For this purpose, the fault-rupture seismic hazard model of Der Kiureghian and Ang (1977) has been implemented in this study, with an improved attenuation equation for the near-source region where very little observed data are available. A near-source attenuation equation has been developed as part of this study based on results obtained through wave propagation in a half-space subjected to a fault-rupture (Seyeddian and Robinson, 1975) and using available relationships between earthquake magnitudes and pertinent parameters of the source mechanism (e.g. Chinnery, 1969).

The lifetime maximum load may occur under the combination of two or more time-varying loads; this may occur during the coincidence of two or more transient loads, such as earthquake and strong wind. In order to include the effect of sustained and other transient loads in combination with earthquakes, improved practical methods for load-combination (including extreme load coincidences) has been developed; the results are derived as the maximum of the sum of several random processes.

Response Determination of Nonlinear-Inelastic Systems

For safety evaluation purposes, the prediction of the response of a structure in the range of severe damage, including impending collapse, is necessary. In this range of interest, structural behavior is invariably nonlinear and inelastic, and in the case of earthquake-induced response the hysteretic characteristics of a structure is also important.

An analytical model has been developed for describing the hysteretic restoring force including the degradation of strength and/or stiffness. This can include systems that may deteriorate as a function of the total hysteretic energy dissipated. Also, a companion stochastic equivalent linearization method has been developed for the random response analysis of single and multi-degree of freedom systems suitable for determining the response of the required nonlinear-inelastic systems. The method can be used to obtain the needed statistics of maximum response, including maximum response probability distribution, that are needed for determining the probability of structural damage. This part of the research is the subject of Professor Wen's report at this meeting, and further details can be found therein.

Seismic Safety Evaluation of Buildings

The tools developed thus far are now being used in a limited evaluation of seismic safety of specific types of structures. In particular, for purposes of demonstrating the potential implementation of the methodology, a typical building structure that may be modeled as a shear-beam system has been considered. Such a safety evaluation involves the following:

(1) The determination of the seismic hazard at the building site; this requires the calculation of the probability of exceedance (or corresponding return periods) of all the ground motion intensity at the site, that may result from all the potential earthquake sources in the region around the site (within a radius of a few hundred kilometers).

(2) For a given intensity (e.g. in terms of maximum ground acceleration), the ground motion may be described as a nonstationary filtered white noise process, using one of the available random process models for this purpose. The pertinent maximum response statistics of a building are determined with the nonlinear-inelastic random vibration method developed herein, including the rms maximum response for the interstory distortion of the building.

(3) Because of uncertainty in the structural parameters, such as strength, stiffness, damping, as well as the hysteresis parameters, the variation in the maximum response as a consequence of variations in these structural parameters must also be reflected in the safety evaluation. Sensitivity coefficients, representing the change in the maximum response due to variations in the structural parameters, are evaluated numerically; from which the coefficient of variation of the maximum response due to uncertainties in the structural parameters can be calculated.

(4) With the information obtained as described above, and prescribing reasonable probability distribution for the maximum seismic response (expressed in terms of ductility factor) as well as for the capacity of the structure (in terms of limiting ductility), the probability of structural damage can be calculated for a given ground motion intensity.

The calculated damage probability is a conditional probability, from which the lifetime failure probability can be obtained by convoluting this conditional damage probability with the corresponding probability of exceedance for all possible ground motion intensities over the life of the structure.

Seismic Hazard and Safety of Lifeline Systems

A lifeline system may be subject to fault-rupture strike during an earthquake, in addition to the hazard of high-intensity ground shaking. In contrast to a building or other similar structures that are essentially point systems and thus the chance of fault-rupture strike may be neglected, the hazard of such strikes on a lifeline system is much more real especially in regions where surface ruptures are likely in an earthquake.

A model for calculating the probability of fault-rupture strikes on a lifeline system has been developed. The evaluation of this hazard as well as the hazard to severe ground shaking have been illustrated for water-distribution systems and major highway networks. A lifeline may be idealized as a system of parallel paths, each of which is composed of links in series. The probabilities of the two modes of failure for each of the links constitute the basic information needed to evaluate the safety of the system in the respective modes of seismic hazard.

Details of this study are described in a report by Mohammadi and Ang (1980).

References

Der Kiureghian, A. and Ang, A. H-S., "A Fault-Rupture Model for Seismic Risk Analysis," Bull. SSA, Vol. 67, No. 4, August 1977, pp. 1173-1194.

Seyyedian, C. M., and Robinson, A. R., "Motion on the Surface of a Layered Half-Space Produced by a Buried Dislocation Pulse," Univ. of Ill. C.E. Studies, SRS No. 421, Nov. 1975.

Chinnery, M. A., "Earthquake Magnitude and Source Parameters," Bull. SSA, Vol. 59, No. 5, Oct. 1969, pp. 1969-1982.

Mohammadi, J. and Ang, A. H-S., "A Method for the Analysis of Seismic Reliability of Lifeline Systems," Univ. of Ill. C.E. Studies, SRS No. 474, February, 1980.

M. ERDİK, P. GÜLKAN, A. GÜRPINAR

Earthquake Engineering Research Institute
Middle East Technical University

This summary outlines an ongoing study regarding the seismic risk analysis of Turkey. The study is supported by the Turkish Scientific and Technical Research Council and it is anticipated that the conclusions will be reflected in future revisions of the seismic hazard map of Turkey.

The study will culminate in iso-intensity and iso-acceleration maps for Turkey and provide maximum intensity and peak ground acceleration contours with different probabilities of being exceeded during selected durations of time.

The associated research steps are :

1. Acquisition of Historic, Macroseismic and Instrumental Data for Seismic Events.

The studies in this step involved compilation of all the data from the existing literature and, for large events, their correlation with the official macroseismic data files. These studies have been presented in Erdik and Özselçuk (1978).

2. Location and Description of Earthquake Sources.

A seismotectonic map of Turkey based on the 1:2 500 000 scale Neotectonic map of Turkey prepared by the Mineral Research and Exploration Institute has been prepared. To outline the seismic sources another seismotectonic map indicating the macroseismically correlated epicenters of earthquakes with magnitudes larger than 5.9 has been adopted. This map given in Fig. 1 is the same as that given by Erdik and Mathur (1979). The primary earthquake sources selected are : (1) the North Anatolian Fault Zone, (2) the East Anatolian Fault Zone, (3) South Anatolian Folds Thrust Front, (4) Marmara Thrace Zone, (5) Western Taurids and various grabens in the Western Turkey.

3. Construction of Recurrence Relationships and Maximum Magnitudes for Individual Sources.

Log-linear earthquake magnitude-frequency relationships have been derived for each source after an artificial homogenization and complementation process for the deficient data in earlier reporting periods. This process, adopted from Stepp (1972), has been found necessary to provide reasonable maximum magnitudes associated with small frequencies of occurrence. The maximum magnitudes associated with lineaments and area sources have been determined, respectively, on the basis of ruptured fault length vs. magnitude correlations and on Gumbel distributions.

4. Selection of Attenuation Equations Based on Regional Characteristics.

Local attenuation equations based on isoseismal maps are obtained to provide the mean intensity at a site for given epicentral distance and earthquake magnitude at the source. The account for the ellipticity of isoseismals associated with the linear sources attenuation equations have been developed for mean distances (i.e. radius of the equal area circle) and the shortest distances to the lineament. These studies have resulted in a number of publications, e.g., Gürpınar et al. (1979).

5. Probabilistic Modeling.

For isolated linear sources the fault rupture model of Der Kiureghian and Ang (1977) and for area and point sources the Cornell (1971) model have been employed. For cases where both types of sources were in close proximity both models were separately implemented and the resulting envelope risk was taken. A comparison of both models for the North Anatolian Fault Zone has been presented in Gürpınar, et al. (1979).

An example of the resulting iso-intensity and iso-acceleration maps is given in Figs. 2 and 3 for the North Anatolian Region. The first one is based on the intensity attenuation of Gürpınar, et al. (1979) and the second one on the peak ground acceleration attenuation of McGuire (1974).

This map will establish a more rational and consistent basis for a seismic hazard map because its contours will represent equal probabilities of seismic exposure. Furthermore, the same rational basis can be easily kept in future revisions of the map as new date becomes available. It is envisioned that the final report will be published in the spring of 1980.

REFERENCES

1. Erdik, M., and A. Özselçuk, "Regional Rearrangement of Earthquake Catalogues of Turkey," Report No. 78-6, Earthquake Engineering Research Institute, Middle East Technical University, Ankara, 1978.

2. Erdik, M., and S. K. Mathur, "Evaluation of Earthquake Hazards - Correlation of Seismic Activity and Tectonic Elements of Turkey," Bulletin of the International Association of Engineering Geology, No.19, 1979, pp. 145-152.

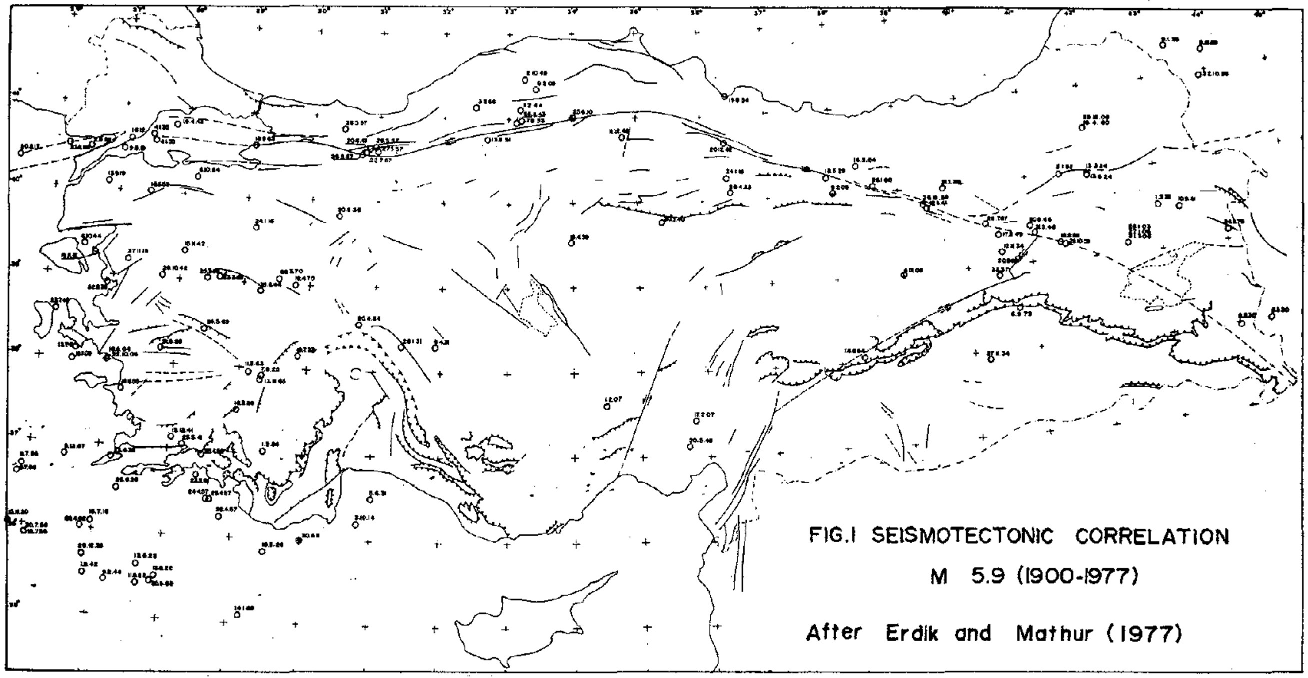
3. Stepp, J.C., "Analysis of Completeness of the Earthquake Sample in the Puget Sound Area and Its Effect on Statistical Estimates of Earthquake Hazard," Proceedings of the International Conference on Microzonation, Seattle, Washington, 1972.

4. Gürpınar, A., et al., "Seismic Risk Analysis of Northern Anatolia Based on Intensity Attenuation," Proceedings of the Second U.S. National Conference on Earthquake Engineering, Stanford University, August 22-24, 1979.

5. Der Kiureghian, A., and A. H.-S. Ang, "A Line-Source Model for Seismic Risk Analysis," Structural Research Series No. 419, Department of Civil Engineering, University of Illinois, Urbana, Illinois, 1977.

6. Cornell, C.A., "Probabilistic Analysis of Damage to Structures under Seismic Loads," Dynamic Waves in Civil Engineering, edited by D.A. Howells, Wiley-Interscience, 1971.

7. McGuire, R.K., "Seismic Structural Response Analysis Incorporating Peak Response Regressions on Earthquake Magnitude and Distance," Report No. R74-51, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1974.



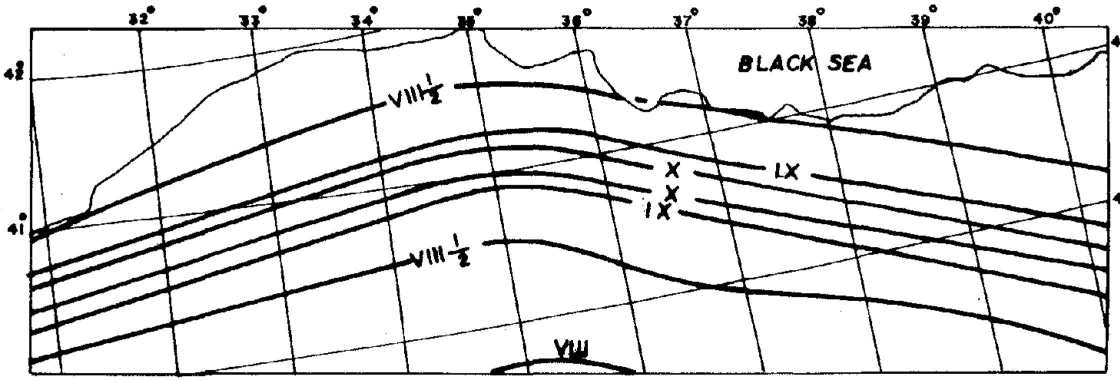


FIG.2 ISO-INTENSITY CONTOURS FOR RETURN PERIOD OF 475 YEARS (After, Gurpinar Et.Al.1979)

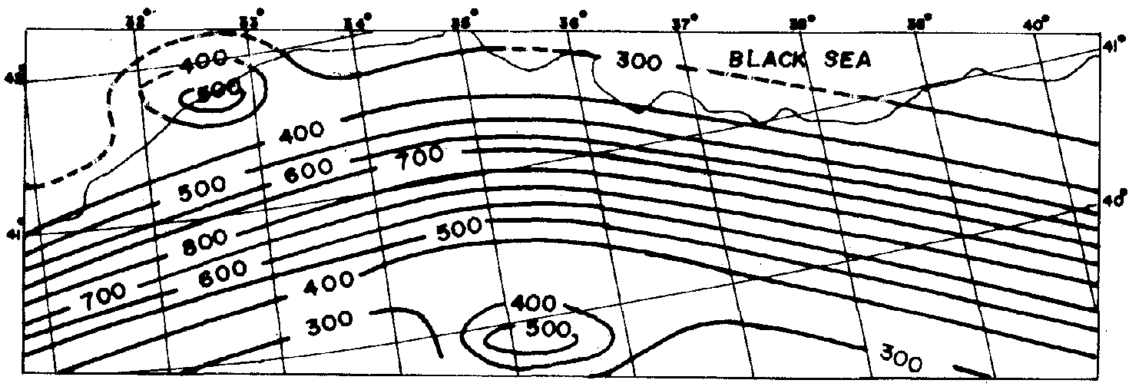


FIG.3 ISO-ACCELERATION CONTOURS FOR RETURN PERIOD OF 475 YEARS

FRANKLIN Y. CHENG

University of Missouri-Rolla

This paper summarizes three research projects currently in progress at the University of Missouri-Rolla. The continuing research efforts in earthquake structural engineering at UMR are supported by the National Science Foundation, the University and others.

Optimality Criteria for Plate Bending Systems and Three-Dimensional Structures with Flexible Diaphragms

There is an urgent need to develop optimization methods for computer-aided design, and these methods should be more rational and reliable than those commonly used in the electronic computations based on conventional trial and error processes. This project is to develop an optimum design technique for plate bending systems and three-dimensional structures with flexible diaphragms. Plate bending systems consist of only plate elements with various boundary conditions, and three-dimensional structures may have bracings, beams, columns, shear panels, and floor diaphragms. The diaphragms are essentially only one of the plate element systems. These two systems will be subjected to multicomponents of static and dynamic parametric constraints. The optimality criteria method and its associated recursion technique will be studied.

The objectives of the above stated project are: 1) To develop a mathematical formulation of an efficient optimum algorithm and a substructural synthesis technique, 2) To develop an associated computer program with analysis and design options, 3) To prepare options in computer codes for typical dynamic forces, ground motions, and building code recommendations, 4) To observe the desirable rib-stiffness distributions based on plate thickness variations of plate element systems, and 5) To study the influence of diaphragm flexibilities on structural response, on the column stiffness requirements at critical regions, and on the overall stiffness distribution of an entire system. It is believed that the undertaken optimization study and the parametric investigation are of paramount importance in many engineering disciplines and that fruitful results can be expected.

ODSEWS (Optimum Design of Static, Earthquake, and Wind Structures) for Plane Steel Structures and ATC-3 Recommendations

This project emphasizes on the inclusion of the design recommendations of ATC-3 of equivalent lateral forces, modal analysis, and soil-structure interaction in the existing ODSEWS computer program.

The current ODSEWS is capable of analyzing and designing trusses, unbraced, single-braced, double-braced, and K-braced frameworks in which the constituent members are bar elements for bracings and truss-members and beam-column elements for columns and girders. The beam-column elements are either the built-up sections or the hot-rolled wide flange sections available in the AISC Steel Construction Manual. The structures can be subjected to static loads, dynamic forces, and horizontal and vertical ground motions as well as the Uniform Building Code. The dynamic forces and the seismic excitations can be used on the basis of either direct integrations or response spectra.

The structural formulation is based on the displacement method and the second-order effect resulting from the static and dynamic forces that act axially on the columns. The behavior constraints are the allowable stresses, displacements, and natural frequencies. Various displacement constraints can be applied to individual nodes with any specific numbers.

After the ATC-3 recommendations are implemented, parametric studies will be emphasized on the effect of various seismic inputs on individual typical structural systems subjected to a given set of constraints.

Design and Assessment of Building Systems for Parametric Multicomponent Earthquake Motions

This project deals with the development of computer-aided design method for three-dimensional building systems. The structural model is similar to the previous work of inelastic analysis of reinforced concrete and steel building systems for 3-D ground motions and has the following characteristics: (1) The structure consists of steel columns, beams, and bracings as well as floor diaphragms, shear walls, and flexural shear panels. (2) The floor and roof diaphragms are idealized as laminae having infinite rigidity in their own planes but flexibility out of them. The diaphragms can be thin, cast-in-place, concrete slabs on open web steel joists or cold formed steel deck panels with concrete placed on them. (3) The structure can be subjected to static vertical loads on beams and joints and lateral loads at the floor levels as well as to three-dimensional interacting ground motions. The mass at each floor produces two transverse and one rotational inertial force as well as vertical inertial forces at each column. The dead load of all the floor masses and their inertial forces, which result from vertical ground motion, induce an overturning moment, which is included in the analysis as the second-order moment of the P-Δ effect.

In addition to static loads and interacting ground motions, the computer program will also include ATC-3 recommendations of equivalent lateral forces, modal analysis, and soil-structure interaction. The assessment of structural parameters will emphasize on the effect of various seismic excitations and the tentative provisions on structural performances.

Related Publications

1. Cheng, F.Y. and D. Srifuengfung, "Optimum Structural Design for Simultaneous Multicomponent Static and Dynamic Inputs", International Journal for Numerical Methods in Engineering, Vol. 13, No. 2, November 1978, pp. 353-372.

2. Cheng, F.Y., "Discussion on Optimality Criteria for Seismic Tall Buildings with Specific Natural Frequencies", Proc. 5th Japan Earthquake Engineering Symposium, Tokyo, November 1978, pp. 1249-56.

3. Cheng, F.Y., K.B. Oster and P. Kitipitayangkul, "Establishment of Ductility Factor Based on Energy Absorption and Evaluation of Present Methods", Proc. 3rd Canadian Conference on Earthquake Engineering, Vol. I, pp. 719-744, June 1979.

4. Cheng, F.Y. and P. Kitipitayangkul, Investigation of the Effect of 3-D Parametric Earthquake Motions on Stability of Elastic and Inelastic Building Systems, Final Report No. 1 prepared for the National Science Foundation under Grant No. NSF 7518372-A01, 1979. Available at NTIS, Springfield, VA 22151.

5. Cheng, F.Y. and P. Kitipitayangkul, INRESB-3D A Computer Program for Inelastic Analysis of Reinforced-Concrete Steel Buildings Subjected to 3-Dimensional Ground Motions, Final Report No. 2 prepared for the National Science Foundation under Grant No. NSF 7518372-A01, 1979. Available at NTIS, Springfield, VA 22151.

6. Cheng, F.Y., "Inelastic Analysis of Dynamic Space Frames", Proc. 7th National Conference on Electronic Computations, American Society of Civil Engineers, 1979, pp. 537-552.

7. Cheng, F.Y. and P. Kitipitayangkul, "Inelastic Behavior of Building Systems to Three-Dimensional Earthquake Motion", to be presented at the 7th World Conference on Earthquake Engineering, September 8-13, 1980 and to be published in Conference Proceedings.

8. Cheng, F.Y., "Energy Distribution Criteria for Braced and Unbraced Structural Design Subjected to Parametric Earthquake Motions", to be presented at the 7th World Conference on Earthquake Engineering, September 8-13, 1980 and to be published in Conference Proceedings.

9. Cheng, F.Y., "Assessment of Optimum Design of Various Static and Dynamic Structural Systems" to be published in the Proceedings of the Canadian Society for Civil Engineering, 1980.

RICHARD W. STEPHENSON, JOHN D. ROCKAWAY

University of Missouri-Rolla

Definition of the Problem

The greater St. Louis area of Missouri and Illinois, one of the largest population centers in the Midwest, is located within 200 miles of one of the most seismically active regions in the United States. This seismic region encompasses a portion of southeastern Missouri, southwestern Illinois, western Kentucky, and northwestern Tennessee and was the location of the greatest sequence of earthquakes in North American history--the New Madrid earthquakes of 1811 and 1812. Since the events of 1811 and 1812, at least 85 earthquakes of Modified Mercalli Intensity (MMI) V or greater (13 earthquakes of MMI VII or greater) have been recorded within 200 miles of the New Madrid area.

In addition to the proximity of the St. Louis area to an active seismic region, other geologic factors exist to add to the potential for damage from earthquakes. First, one of the distinguishing features of Central United States earthquakes is their large area of perceptibility of ground motion as compared to those in the West (Nuttli, 1972). Secondly, the urban expansion has extended onto thick lucustrine and alluvial deposits along the Mississippi and Missouri Rivers and their tributaries, as well as over thick loess deposits on the uplands.

Scope and Objectives

In 1978 the United States Geological Survey awarded a research grant to the University of Missouri-Rolla for the purpose of conducting a pilot study to analyze the potential of earthquake-induced geologic hazards in a portion of the Creve Coeur Quadrangle in St. Louis County, Missouri. The primary objectives of the research were to provide an appraisal of the relative levels of individual seismic hazards in the form of zoning maps at detailed scales, and to assess the significant hazards for the study area. The format of the zoning maps was to be useful to engineers and architects, as well as government officials, planners, and others involved in land-use planning.

As part of that research, a review of the regional geology and seismicity, as well as an estimation of bedrock motions from the maximum expected earthquakes in the surrounding region, was completed by Bauhof (1979). The design earthquakes chosen consist of a near field, high frequency Ozark Uplift earthquake and a far field, low frequency New Madrid Region earthquake. The design earthquakes were selected to represent the maximum bedrock motion expected at the study site in terms of peak horizontal acceleration, peak horizontal velocity, predominant period, and bracketed duration. Existing acceleration time-histories were modified to match these ground motion parameters to produce the design earthquake accelerograms. A field exploration program also was undertaken to establish the soil stratigraphy, depth to bedrock, depth to ground water, and to collect quality soil samples for laboratory analyses of engineering properties.

For this study, the appraisal of the relative levels of individual seismic hazards was accomplished by inputting the selected design earthquakes and the static and dynamic properties of the soil deposits into the SHAKE computer analysis to determine the modification of the ground response from the various soil deposits at the study site. The resulting ground response data, combined with the static and dynamic material properties and data on thickness, topography, and ground-water levels were used to determine the susceptibility of the unconsolidated units to seismic-induced geologic hazards. The relative potential for failure of these units was evaluated on the basis of computed factors of safety for the different levels of ground motion.

The result of this study was the development of a set of maps which shows the potential for slope failure, liquefaction, and damage to structures from ground motion in the event the maximum expected earthquake were to occur. Since the maps are based on state-of-the-art analytical methods and engineering hazard evaluations, they should be useful in the planning, development, and design of new structures in the rapidly growing Creve Coeur area. In addition, the research has led to the development of systematic techniques for appraisal of individual seismic hazards. This method of seismic hazard analysis is believed to be an improvement over existing procedures since it incorporates both quantitative engineering data and qualitative geologic data.

Computer Mapping Procedures

The University of Missouri-Rolla Geological Engineering Department's digital image processing system was used to evaluate and map the earthquake hazards. The computer program used was modified from an existing seismic mapping program developed at the Nevada Bureau of Mines and Geology (Bell, et al., 1978).

The mapping program used was a modified version of the hazard model for the Reno, Nevada, area. It is based on phenomenologic and probabilistic data incorporating available geologic and engineering information. The program assessments are based on major factors that influence seismic-induced hazards, including: properties of the unconsolidated geologic units, depth to bedrock, slope of terrain, depth to ground water, etc. The date defining these factor are digitized to form basic data files for seismic response, slope, depth to ground water, etc. These parameters are evaluated for a geographic area based on a matrix with a cell as the fundamental unit of evaluation and digitization. The basic data digitized for each cell represents the predominant condition in that cell. The parameters for each cell are assigned integer values to represent their relative magnitude, and these values are digitized for the matrix. The individual hazards maps are constructed by algebraic summation of the digitized values in the seismic response classification with each of the other basic data files. The hazard assessment is aided by the fact that each parameter in the data base can be ranked individually according to its contributing effect on the total seismic hazard.

Parameters digitized to form the basic data fields for this study included the maximum horizontal acceleration response, the velocity response spectrum, areas of saturated sandy deposits susceptible to liquefaction, and the slope of the terrain. The digitization of these parameters was based on assigned interger values which represent the relative magnitude of the predominant condition within a 400x400-foot cell. The cell size was chosen on the basis of the desired detail of the individual data files and was considered small enough to provide a realistic representation of the seismic hazards at a map scale of 1:24,000.

Digitization of the ground response was based on the maximum acceleration response, computed by analytical methods, of generalized soil profiles which were constructed to represent the soil stratigraphy of the study area. The response is dependent on the properties of the soils composing the unconsolidated deposits, the deposit thickness, and the characteristics of the base motion; therefore, each soil profile had characteristic response to each design earthquake. The soil profiles were assigned interger values for digitization on the basis of their relative magnitude of response to the base motion. The input of ground response actually produces two maps--a maximum acceleration map providing data for calculation of factors of safety against liquefaction and slope instability, and a damage potential map based on the velocity spectrum for a given range of fundamental periods.

The data image for the ground response was displayed on the Comtal screen, areas of similar acceleration response and velocity response were grouped by use of a color table, and then labeled and written on magnetic tape for generating a gray scale plot.

Areas of saturated sandy deposits with a high water table and low relative densities were digitized into a liquefaction susceptibility data file. The digitization was based on the magnitude of horizontal accelerations needed to cause liquefaction. The liquefaction susceptibility data file was then superimposed with the maximum acceleration data file. Where horizontal accelerations equaled or exceeded those calculated to cause liquefaction, the area was delineated as having a liquefaction hazard. Areas of greater potential were separated from areas of less potential. The liquefaction potential was assessed on the Comtal screen, areas of similar liquefaction potential grouped by use of a color table, assigned similar symbols, and written on magnetic tape for plotting.

For the potential slope hazards evaluation, the degree of slope was digitized into a gridded data file on the basis of a range of slope and corresponding yield accelerations. The slope file was superimposed on the maximum acceleration data file, forming a slope hazards map. Areas where yield accelerations were equaled or exceeded were assessed on the Comtal screen, identified by use of a color table, assigned symbols, and written on magnetic tape for gray scale plotting.

With the completion of the hazard assessment, the maps were recalled from tape and plotted at a scale of 1:48,000 on the Varian printer-plotter. The resulting maps delineate areas of geologic hazards and levels of ground response from earthquakes similar in magnitude to the design earthquakes.

T. E. BLEJWAS

Oklahoma State University

This paper summarizes current research being conducted by the author at Oklahoma State University in the area of damageability of existing buildings. The research is a continuation of work started by the author at the University of California, Berkeley and sponsored by the National Science Foundation.

Damageability of Existing Buildings

The need for hazard abatement in buildings is clear. In order to establish priorities for rehabilitation, demolition, or further detailed evaluation, methods of evaluation that are simple but meaningful are required. The performance of buildings during recent earthquakes emphasizes the need for reliable methods of evaluating potential damage and hazard. The goal of the present research is to develop the methodology for assessing potential damage (damageability) that is simple to implement, reliable in that verication is possible, and flexible enough to be easily modified to account for changes in criteria, local conditions, and improvements in modeling.

Damageability Indices

Damageability indices are being used to quantify the degree of potential damage. Local indices which represent the damageability of elements or parts of the building are combined to form a single global index which represents the degree of damageability of the entire building. The local index for each element is assumed to be a piecewise linear function of a demand parameter which is available from a response analysis. The index goes linearly from zero to one as the demand parameter goes between values of capacity for initial and total damage. The global damageability index is a weighted sum of local indices with importance factors used for weighting. The global index is normalized such that zero indicates no damage and one is complete, unrepairable damage. Research is continuing to determine more complete guidelines for estimating the capacities of structural and nonstructural elements in terms of demand parameters. Also, importance factors are being studied to determine meaningful relative values.

Response Analysis

To assess the damageability of a building, the probable response of the structure to future earthquakes must be estimated. Static analyses used for design are generally not suitable for damageability assessment. Time-history nonlinear response analyses are not necessarily justified for evaluating a large inventory of buildings. A form of quasi-static nonlinear analysis is presently being investigated for low-rise to medium-rise structures. The procedure utilizes a force distribution of constant shape which allows the force-displacement relationship for the structure as a whole to be represented in terms of a single coordinate. Comparisons with inelastic response spectra provide estimates of maximum response from which damageability can be assessed.

Goals of the current research are to attempt to verify the approximate response procedure and to implement a modified procedure in which the force distribution is updated during the response analysis; in this way commonly observed softening effects may be better represented.

W.G. MILNE

Pacific Geoscience Centre

Research Programs Related to the Canadian Seismic Probability Map

Scientists at the Earth Physics Branch in Ottawa and at the Pacific Geoscience Centre are continuing research programs to improve the 1970 edition of the seismic zoning map contained in the National Building Code of Canada. Published ground motion data have been fitted by numerical methods to functions relating amplitude, magnitude, and distance. In general, it is found that regressions of magnitude and distance with peak or sustained acceleration, velocity, and response amplitudes provide similar sets of curves over several frequency ranges which are related by simple factors. The introduction of a constant term in addition to depth of focus in the distance parameter is not needed to obtain a good fit to the data. The function has the form

$$A = K\, e^{aM}\, R^{-b}$$

where A is amplitude, M is magnitude, and R is hypocentral distance. Based upon accelerograph data in the west, but intensity data in the east, the b parameter of the distance term is 0.2 units lower in the east.

In addition to the research on ground motion parameters, the identification and study of active seismic zones is continued. In the western region the seismic zones which are defined by historical seismic activity combined with identified tectonic regions are Queen Charlotte, Sandspit, Offshore, Northern Vancouver Island, Coast Mountains, Cascade, Puget Sound, Southeastern British Columbia, and Northern British Columbia. Within each, a set of earthquakes, complete for magnitude ranges identified with a range of years of observations, are analysed to obtain the relationship between magnitude and frequency of occurrence.

With these parameters, the research will proceed to the drawing of a seismic zoning map by methods similar to those used for the ATC-3 map.

MARK FINTEL and S. K. GHOSH

Portland Cement Association

Introduction

Economic considerations usually dictate that the large seismic energy inputs to most buildings be absorbed and dissipated through inelastic deformations. Modern building codes recognize this necessity and prescribe designs based on anticipated inelastic behavior. However, owing at least in part to a lack of simple inelastic procedures, the analysis of the internal forces in the structure is usually carried out assuming elastic behavior, under specified static loads applied to the mass locations of a structure. The member forces so determined may bear only a nominal resemblance to internal forces that result from an actual inelastic earthquake response of the structure. Also, the distribution and magnitude of inelastic deformations in various structural members cannot be determined through elastic analysis under Code-specified static loads. As a result, ductility has to be supplied throughout the entire structure, although inelasticity may actually occur only in certain levels and locations.

This research proposes an alternative seismic design approach which represents a significant departure from the empirical Code approach. The suggested procedure uses earthquake accelerograms as loading, dynamic inelastic response history analyses to determine member forces and deformations, and resistances from tests for proportioning the members.

Explicit Inelastic Dynamic Analysis and Proportioning

Two-dimensional dynamic inelastic (response history) analysis computer programs, incorporating proper hysteretic characteristics of reinforced concrete and steel members, have recently been developed. With such programs, it is now possible to perform a realistic analysis of the earthquake response of multistory concrete and steel structures at a reasonable cost. The suggested design procedure is based on such analyses, and entails:

1. Preliminary layout and design of the structural system based on gravity as well as Code wind and earthquake loads.

2. Modeling of the structure for dynamic analysis in each of two orthogonal directions, and determination of the natural undamped periods of the structure in each direction.

3. Selection, on the basis of local seismicity and of structural and soil characteristics, of a design earthquake accelerogram which will critically excite the structure.

4. Determination of forces and deformations in all members under the design earthquake, using inelastic response history analyses.

5. Proportioning of members for strength and deformability in the elastic and post-elastic ranges, based on resistances known from tests.

6. Checking that the structure will survive without collapse an hypothetical maximum credible earthquake, which is considerably more severe than the design earthquake.

Advantages of the Proposed Approach

The following advantages will result from the application of the inelastic dynamic approach:

1. The magnitude and location of inelastic deformations can be determined, so that ductility details need to be provided only where required.

2. A desirable balance between the strength and ductility requirements of individual members can be designed into a structure.

3. A predetermined sequence of plastification can be designed into a structure. The beams, for example, can be made to yield before the columns.

4. The two-level earthquake input motions approach permits specifying different performance criteria for the two levels of seismic response. For example, inelasticity may be permitted only in horizontal members during the design earthquake, and also to a limited extent in vertical members under an hypothetical maximum credible earthquake.

5. The earthquake resistance of structural walls can be fully utilized. Recent investigations have definitely demonstrated that structural walls are ductile when properly proportioned and detailed.

6. The designer can creatively devise various structural configurations and distribute the energy dissipating elements where they will be the most effective without endangering the stability of the entire structure.

Current Research - Design Examples

A number of design examples using the proposed approach have been worked out[1-4]. Work on several other design applications is currently in progress. The purpose of this research is to determine and demonstrate the applicability of the proposed inelastic approach to various structural systems in steel and concrete, and to arrive at an in-depth assessment of the advantages and limitations of the proposed approach.

Work aimed at improving certain aspects of the proposed design procedure is also in progress. These aspects include: a) selection of the critical input motion for dynamic analysis, b) analytical modeling of the inelastic regions of structural members, and c) proper definitions of deformation demand and deformation capacity, as well as a meaningful correlation of the two quantities.

References

1. Fintel, M., and Ghosh, S.K. "Inelastic Aseismic Design of R. C. Wall Structures," Preprint 3589, ASCE Convention and Exposition, Boston, Mass., April 1979.

2. Fintel, M., and Ghosh, S.K., "Explicit Inelastic Dynamic Analysis and Proportioning of Earthquake-Resistant Reinforced Concrete Buildings," Proceedings of the second U.S. National Conference on Earthquake Engineering, Stanford, Calif., August 1979, pp. 393-402.

3. Fintel, M., and Ghosh, S.K., "Seismic Resistance of a 16-story Coupled-Wall Structure: A Case Study using Inelastic Dynamic Analysis," Engineering Bulletin 82, Portland Cement Association, Skokie, Ill., 1980, (to be published).

4. Fintel, M., and Ghosh, S.K., "Seismic Resistance of a 31-Story Shear Wall-Frame Building using Dynamic Inelastic Response History Analysis," Proceedings, Seventh World Conference on Earthquake Engineering, Istanbul, Turkey, September 1980, (to be published).

HARESH C. SHAH
ANNE S. KIREMIDJIAN

Stanford University

One of the major efforts in seismic risk analysis studies is the reassessment of all currently available empirical and geophysical models and procedures. Empirical techniques of modeling strong ground motion have come under close scrutiny in recent years. The large uncertainty in these models has raised questions about the parameters used to characterize seismic events and about the modeling techniques themselves. In the research currently under progress, close consideration is given to the source mechanism of the event and a more reasonable distance measure (other than the epicentral distance) is studied. The root mean square (RMS) acceleration as a ground motion parameter is suggested for use in characterizing the intensity of strong ground motion. A Bayesian approach is used to combine empirical, theoretical and subjective information. In conjunction with this study, the necessary step of defining the "significant" duration of the record is investigated. The intent of this specific study is to synthesize and convolve all the theoretical seismological models, empirical models and subjective input on ground motion estimation into one rational and physically more representative methodology.

Associated with the above general objective, a detailed statistical analysis of the available strong motion data is carried out. The purpose of such an analysis is to understand the statistical distribution of recorded peaks. Variables relating this peak value distribution to source and site characteristics are the magnitude, effective distance, site condition and the overall site filtering characteristics.

Various earthquake occurrence models needed in seismic risk studies, are also investigated. These models include the homogeneous and nonhomogeneous Poisson models as well as Markov chain models. In the nonhomogeneous Poisson model, the rate of occurrence of earthquake events for a given source is assumed to be dependent on time since the last event. This is a better assumption than the homogeneous time independent rate of occurrence assumption. A further refinement is introduced through Markov chain model where spatial and temporal dependence of events is considered. Such a model can properly represent the seismic gap as well as seismic clustering phenomenon.

An important aspect of seismic risk analysis is the loss and damage assessment. Procedures for systematically identifying parameters affecting the damage potential and evaluating this potential is being developed. Such an assessment is necessary for insurance studies and for regional loss and damage impact studies for public policy issues. Through such studies, earthquake disaster mitigation policies can be formulated.

On the public policy side, some recent work at the center evaluated the issues of earthquake prediction and earthquake engineering. A micro and macro economic model was developed to assess the costs and benefits associated with the two options available for mitigating future earthquake damage.

A detailed study is also underway to investigate seismic risk analysis of lifelines and other infrastructural systems. The central subject is the determination of the likelihood of attaining various levels of system impairment and what to do with that information. System oriented procedures are developed to study the impact of an earthquake on spatially distributed systems.

Researchers working on these projects are: Dr. Martin W. McCann, Jr.; Dr. Milton DeHerrera; Dr. Katsuhiko Ishida; Dr. Christian Mortgat; and Mr. Hector Monzon.

The projects are supported by the National Science Foundation, U.S. Geological Survey and the John A. Blume Earthquake Engineering Center.

S. F. BORG

Stevens Institute of Technology

A fundamental invariant for the earthquake phenomenon is studied in this Report. The analysis presents a rational analytical representation for the isoseismal map, which is one of the key sets of data for an earthquake. Five separate earthquakes in different parts of the world, which occurred over the past 100 years, are used to check and correlate the data. The invariant obtained in this research is of basic importance in energy analyses of the earthquake event and may find use in studies of the earthquake mechanisms as well as in applications to the practical structural design. In addition, it introduces new parameters that may be of importance in earthquake studies.

The Isoseismal Invariant

An overall consideration involved in this research is an attempt to determine the significant parameters involved in one particular set of earthquake engineering data -the isoseismal map. In this map regions of equal intensity are bounded by curves. There is no doubt that the location of the regions of different intensity is somewhat arbitrary and subject to the data-taker's interpretation. However, it is an important, recognized set of earthquake engineering data. It would therefore be very desirable that some generalization or invariant or parameter or correlation be developed from this data and the present report addresses this problem.

On purely physical grounds, it would seem reasonable that a measure of the earthquake strength -or of its energy- is connected with the intensity number and the area over which this intensity number acts.

Thus -as a first step in the development of the model, it was assumed that the isoseismal curves may be represented by equivalent area circles. Admittedly, some of the isoseism representations are highly assymetric. These are probably due to linear surface or near-surface faults. Deep focus earthquakes probably generate more nearly circular isoseisms. In any case, an average circular representation can be taken as a first step and its validity checked against the realities of actual earthquakes-including the inevitable discrepancies and differences inherent in the determination of accurate isoseismals.

Having made the initial "circular assumption", it is then assumed that a basic parameter for the isoseismal analysis is the product of "intensity times average radius to the region of constant intensity". Physically, this is reasonable. The product (IS_{AV}) or simply (IS) is one measure of the localized energy generated by the earthquake. We shall call this term the Intensity Index.

The mathematical development of the invariant is also a reasonable one -on physical as well as mathematical grounds. It is based upon a development described in Borg, 1974 and leads finally to the equation

$$\frac{\Sigma(IS)}{\Sigma(IS)_f} = e^{K\left[1-\left(\frac{S_f}{S}\right)^n\right]} \qquad (1)$$

in which

$\Sigma(IS)$ is the summation of this quantity from S=o (the epicenter) to the given Intensity region

$\Sigma(IS)_f$ is the total or final value from I_{MAX} to I=3, which is about the lowest Intensity reading possible

K and n are constants to be determined by studying actual earthquake isoseismal maps.

To test this invariant hypothesis, the published isoseismals of the following earthquakes were utilized: 1) San Fernando, Feb. 9, 1971, 2) Friuli, May 6, 1976, 3) Udine region, June 29, 1873, 4) Washington State, Dec. 14, 1872, 5) Imperial Valley, May 18, 1940. It was found that a good fit for all five earthquakes is given by

$$\frac{\Sigma(IS)}{\Sigma(IS)_f} = e^{2\left[1-\left(\frac{S_f}{S}\right)^{1/3}\right]} \qquad (2)$$

The two fundamental parameters are S_f and $\Sigma(IS)_f$ and an analysis based upon a tentative uniqueness-existence hypothesis leads to the conclusion that 1) S_f is influenced by soil or geological conditions 2) $\Sigma(IS)_f$ is influenced by the surface horizontal energy of the earthquake.

Finally, an extension of the mathematical analysis leads to the conclusion that the total surface horizontal energy per unit radius attenuates inversely as the $S^{1/3}$ power.

All of the above is covered in detail in the report mentioned in the Acknowledgement and further study is in progress in checking and attempting to verify the different predictions which follow from the theory.

Acknowledgement

This research was supported by a National Science Foundation Grant No. PFR 7822846. The complete, detailed study is contained in Borg,1979.

Reference

S.F.Borg - Similarity Solutions in the Engineering, Physical-Chemical, Biological-Medical and Social Sciences, Proceedings of Symposium "Symmetry, Similarity and Group Theoretic Methods in Mechanics", Ed. P.G. Glockner and M.E. Singh, Univ. of Calgary, Aug. 1974, pp. 263-282.

S.F.Borg - An Isoseismal-Energy Correlation for use in Earthquake Structural Design, Technical Report ME/CE-792, December, 1979, Stevens Institute of Technology.

STRUCTURAL RESPONSE, EXPERIMENTAL

MICHAEL W. DOBBS

ANCO Engineers, Inc.

This paper summarizes current research at ANCO Engineers, Inc. to promote dam integrity and dam safety. The research is sponsored by the National Science Foundation.

The goal of the project is to promote dam safety by developing a field portable dynamic test method for the acoustic analysis of dams. The dynamic properties and acoustic emissions of dams will be monitored to detect defects which could cause dam failure under extreme load conditions.

This dynamic test procedure will be developed by (1) conducting research in acoustic emission monitoring of concrete, in forced vibration testing of dams, and in finite element dynamic analysis of dams and (2) integrating the results of the research in these three areas and provide a quantitative assessment of dam integrity and dam safety.

Literature searches for dam failure mechanisms and discussions with representatives of the United States Water and Power Resources Service reveal the following: (1) most dam failures occur at initial filling and (2) most dam failures occur as a result of foundation failure.

These facts suggest (1) that acoustic emission monitoring has proof test application during first filling analogous to acoustic emission proof testing of pressure vessels and (2) that periodic acoustic emission monitoring and dynamic property monitoring has application to detect local dam face defects (zones of high stress, zones of cracking and regions of deteriorated concrete) and application to detect global defects (foundation and embankment instabilities).

The results of preliminary research in each of the three project areas are subsequently discussed. Additional research areas are also discussed.

Preliminary Results

Acoustic emission monitoring. Acoustic emissions of metallic structures have been extensively studied. However, acoustic emission of concrete has received comparatively little attention; therefore, it is necessary to perform both (1) laboratory tests on concrete specimens to distinguish between compressive failure of the concrete, tension failure of reinforcing bars, and concrete cracking and (2) field tests to locate zones of high stresses and regions of cracking and deterioration on the dam face.

A series of preliminary laboratory tests on reinforced concrete beams has been performed. The tests were done in both three and four point bending. The amplitude of the acoustic emission and the total number of acoustic emission events were recorded with a single transducer having a 125 kHz - 250 kHz bandpass filter.

The most conclusive result of these preliminary tests was the confirmation of the Kaiser effect in concrete. The Kaiser effect is a phenomenon in which acoustic emissions are observed on loading but no acoustic emissions are observed on unloading and subsequent reloading until the previously attained maximum load is exceeded. Acoustic emission on reloading before the previously attained maximum load is exceeded suggests a deterioration in structural integrity.

A test to measure the attenuation of the amplitude of acoustic emission in concrete was also performed. The attenuation as a function of distance and a function of transducer resonant frequency was measured. These preliminary tests indicate that a 10 to 15 foot radius circle of the dam face could be adequately monitored using a transducer with a 140 kHz resonant frequency. And a 20 to 30 foot radius circle could be adequately monitored using a transducer with a 35 kHz resonant frequency. These tests will aid the transducer placement planning.

Dynamic testing of dams. A forced vibration test of Florence Lake Dam located in the Southern Sierra Nevada in California has been performed. Florence Lake Dam is a multi-arch dam having 58 barrels. The MK-13 eccentric mass sinusoidal shaker designed and constructed by ANCO was used to measure resonant frequencies and map response shapes of three of the 58 barrels. The MK-13 shaker has a maximum force output of 8,000 lbs. Equipment malfunction prevented acoustic emission monitoring.

Four candidate dams for a subsequent forced vibration test have been inspected. The candidate dams are Big Dalton Dam (multi-arch), Morris Dam (gravity), Big Tujunga Dam (single-arch), and Pacoima Dam (single-arch). To aid in the development of this test plan, Southern California Edison (SCE), the Southern California Metropolitan Water District (MWD), and the Los Angeles County Flood Control District (LAFCD) has given ANCO permission to test these candidate dams as well as other dams under their jurisdiction.

Accelerometers will be mounted on the downstream dam face to measure resonant frequencies and to map mode shapes. Up to eight low frequency acoustic emission transducers will be used for initial source location. A smaller array of high frequency transducers will be used for more precise source location and for source monitoring.

Dynamic analysis of dams. A linear elastic dynamic analysis of the selected candidate dam will be performed. The calculation of stresses due to hydrostatic, gravity, and shaker loads will allow prediction of probable zones of high stresses and cracking and will aid in acoustic emission transducer placement. The calculation of resonant frequencies and mode shapes will aid in forced vibration test planning and accelerometer placement. The structural model will also be used to perform seismic analysis and to determine the effect of detected defects on dam integrity and safety under extreme loads.

The arch of the dam will be modeled using variable node continuum elements and the foundation will be modeled using one or more layers of eight node solid elements. Reservoir effects will be included initially using Westergaard's added mass theory.

Additional Research Areas

Funds are being solicited for two additional tasks. These tasks are: (1) high level forced vibration testing of Monticello Dam; and (2) added mass theory verification.

High level testing of Monticello Dam. To promote the understanding of dam dynamics and to promote dam safety, and United States Water and Power Resources Services has given ANCO initial approval to perform high level tests of Monticello Dam. Monticello Dam is a 304 foot high single-arch dam located near Sacramento, California. Monticello Dam will be tested using the MK-15 dual unit eccentric mass sinusoidal structural shaker.

The dual unit MK-15 shaker was designed and constructed by ANCO and is the largest field portable structural vibrator in the world. The dual unit MK-15 has a maximum force output of 250,000 lbs in the frequency range of 2.5 to 30.0 Hz.

Preliminary calculations show that testing of Monticello Dam with the dual unit MK-15 shaker will, at maximum force output, result in a dam crest acceleration response of 0.1 to 0.15 g and a displacement response of 0.1 in. These high level tests, with response levels approaching those due to moderate earthquakes, will make important contributions to: (1) the documentation of damping; (2) the documentation of acoustic emission events; and (3) the verification of dynamic analysis to predict dam response to moderate level earthquakes.

Added mass theory verification. The increase in effective mass due to the reservoir is currently predicted using Westergaard's added mass theory. However, predicted frequencies calculated ignoring added mass effects are often closer to measured frequencies than predicted frequencies calculated ignoring added mass effects.

Westergaard's theory will be quantitatively evaluated by a combined testing and analysis program. Testing of the dam with an empty reservoir will be used with formal nonlinear parameter identification methods to minimize finite element modeling errors and to give a verified empty dam model. The results of a re-analysis of the verified model with added mass to account for the reservoir will be compared to a forced vibration test of the dam with a full reservoir. Discrepancies between the predicted results of the revised model with added mass and the measured values will be due primarily to errors in Westergaard's theory. Formal parameter identification will then be performed to calculate added masses which minimize the error between the measured and predicted frequencies.

V. V. BERTERO and A. E. AKTAN

University of California, Berkeley

Integrated analytical and experimental research on the seismic behavior of reinforced concrete coupled shear walls is summarized. This is a part of ongoing research sponsored by the National Science Foundation on "The Seismic Behavior of Structural Components" at the University of California, Berkeley.

Seismic Behavior of R/C Coupled Walls

General. Reinforced concrete structural walls are commonly incorporated in the structural systems of medium-tall to tall buildings as an effective means of reducing interstory drifts. In certain applications, two or more structural walls are used in the same plane of the walls. Even in cases where these walls are assumed and designed to act as isolated walls, they are actually coupled by the floor system. In a significant number of applications, special coupling girders are used to deliberately utilize a coupled structural wall system. The advantages and the problems created by the use of coupled structural walls for seismic-resistant design of buildings have been discussed in Ref. 1. The inherently increased lateral stiffness and redundancy of a coupled system promise significant advantages over the isolated wall-frame systems, in all the serviceability, damageability and collapse limit states of seismic response.

While the behavior of the components of a coupled wall system, i.e., the walls and the coupling girders, can be estimated from research on these walls acting as isolated walls and on the behavior of girders of ductile moment-resisting frames, coupling of reinforced concrete structural walls with stiff and strong girders substantially affects the seismic response, and therefore demands, of the individual walls when compared with their behavior if they act as independent (isolated) members. The reversing axial force demand on the walls introduced by the shear resistance developed by the coupling girders and the demands on hysteretic energy dissipation of the coupling elements are quite different than in cases where isolated walls and frames are utilized.

Present seismic code requirements for the analysis and design of coupled wall structural systems are highly questionable [1]. This is not surprising in view of the lack of reliable experimental data and corresponding analytical studies. This lack of information is the basic motive behind the present research which has the ultimate objective of developing practical methods of seismic-resistant design for coupled wall systems and particularly combined frame-coupled wall systems. To achieve this objective, integrated experimental and analytical studies are conducted.

Analytical Studies. The main objectives of these studies are (1) to obtain information enabling the planning of required experimental studies (design of testing facility, selection of models, selection of critical loading program, design of instrumentation and acquisition data systems, etc.); (2) to improve present analytical methods of predicting the seismic behavior of frame-coupled wall systems; and (3) to develop practical seismic-resistant design methods for these systems.

To achieve the first objective, a series of studies is being conducted on the following basic parameters: (1) effects of different modeling assumptions in conjunction with available linear and nonlinear dynamic response analysis programs on the simulated dynamic responses; (2) the distribution and magnitude of story shear demands and their time histories corresponding to a number of recorded ground motions and analytical prototype coupled structural wall-frame systems; (3) an assessment of the effects of the relative strength, stiffness and hysteretic behavior between the coupling elements and walls on seismic responses of the coupled wall system.

Experimental Studies. These studies are pursued to assess the effects of (1) the stiffness, strength and detailing of the coupling girders and contribution of floor slab on the behavior of the walls and of the overall system; (2) the design and detailing of the edge members and wall panel on the response of the wall system; (3) the addition of beams at each floor level to frame each story wall panel; and (4) the flexibility of foundations. Furthermore, emphasis will be placed on obtaining the information required to improve analytical modeling of these walls, such as the contribution of the flexural, shear and axial deformations of the wall and coupling girders on the behavior of the system, as well as the effect of cracking and loading and/or deformation reversals on the strength, stiffness, and energy absorption of each of the components of the system.

Summary of Work Accomplished. A comprehensive survey of the literature on the observed post-earthquake responses of medium-tall to tall structures incorporating walls has been concluded, covering the documented earthquakes of the last two decades, as well as a survey of existing analytical and experimental research on isolated structural walls, coupling elements and coupled walls. A preliminary evaluation of the implications of the experimental results obtained on isolated walls and coupling girders has been completed [1].

A 15-story prototype structure incorporating coupled walls has been selected and designed in accordance with both UBC-73 [2] and UBC-79 [3] provisions, as the first subject of the analytical and experimental phases of the research. Several linear and nonlinear static and dynamic analyses have been conducted on the 15-story prototype structure designed according to UBC-73 [2,4]. Based on the results obtained in these analyses, a test setup which can accommodate one-third scale models of four-story subassemblages of three-bay coupled walls has been constructed (Fig. 1). Also, the required loading and data acquisition systems have been designed and are being tested on a dummy specimen.

Special force transducers capable of independently measuring axial and shear forces as well as bending moments in the midsection of the coupling girders were developed and tested. The use of these transducers are considered necessary to determine the amount of axial and shear forces each of the walls carries at any time during its hysteretic behavior. This information is essential for estimating the effects of wall axial forces on their cracking and therefore on the variations of their flexural and shear strength and stiffness.

The first test specimen will be a one-third scale four-story subassemblage of the prototype coupled wall system (Fig. 1) designed in accordance with the UBC-73 code provisions. The loading histories for the lateral and vertical load sources are under study through the analytical nonlinear seismic response analyses of the prototype [3,4].

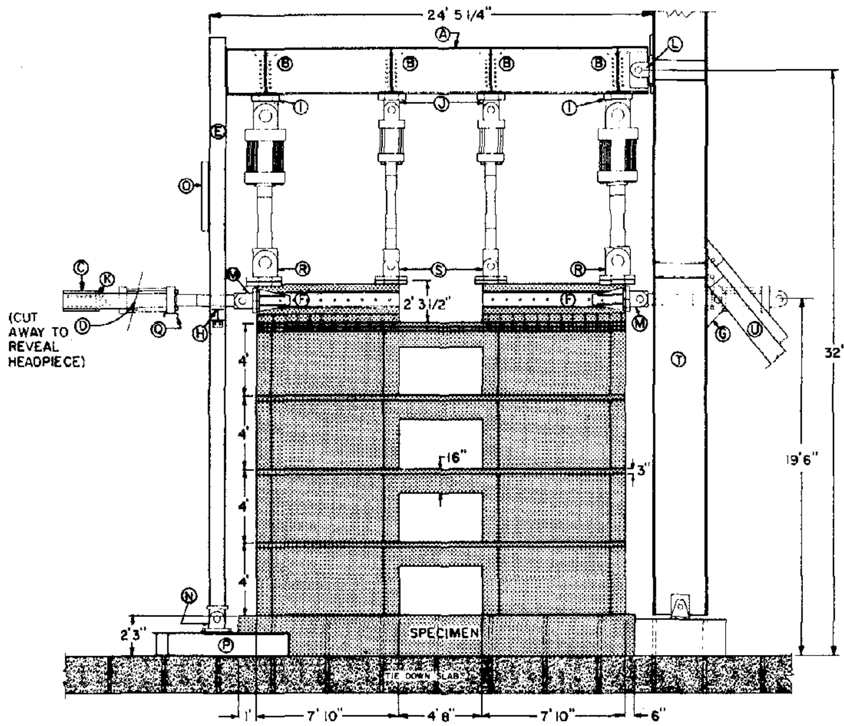


Fig. 1 Test Setup and Specimen

References

1. Bertero, V. V., "Seismic Behavior of R/C Wall Structural Systems," Proceedings of the 7th World Conference on Earthquake Engineering, Istanbul, 1980.

2. Lee, L., and Bertero, V. V., "Testing Facility for Coupled Shear Walls," Earthquake Engineering Research Center, In-House Report, University of California, Berkeley, Feb. 1977.

3. Aktan, A. E., and Bertero, V. V., "The Seismic Behavior of R/C Coupled Shear Walls," Report in progress to be submitted to the National Science Foundation.

4. Tong, S. T., "Behavior of R/C Coupled Walls," Individual research report, SESM, University of California, Berkeley (in preparation).

S.F. STIEMER and W.G. GODDEN

University of California, Berkeley

This paper summarizes current research being conducted at the Earthquake Research Center, University of California, Berkeley in the area of experimental studies on the seismic response of piping systems in nuclear reactors. It is part of a multi-phase project into the design problems of such systems subjected to both thermal and seismic loading, and is sponsored by the U.S. Department of Energy. The overall project consists of analytical studies, metallurgical studies, energy absorbing device design, and shaking table tests, and the work is being done in close consultation with an industrial advisory group from the nuclear industry.

General

The seismic safety of piping systems in nuclear power plants represents a major design problem. The systems are complex in layout, they typically include pipes varying in internal diameter from 0.5 to 30 in, they must be supported in such a way that large displacements due to thermal cycling can readily be accommodated without overstraining the pipes and at the same time retain their integrity under the conditions associated with seismic excitation. The thermal and seismic conditions represent conflicting design requirements. The former calls for a minimum of thermal restraint so that the piping is free to move with the minimum of stress due to self-straining; the latter calls for a maximum support relative to the ground to minimize dynamic seismic stresses.

Current design procedures separate these two effects by frequency and introduce velocity-dependent devices that permit the slow displacements associated with temperature change without inducing significant forces, but that effectively lock and prevent pipe displacement at the point of connection at the high frequencies associated with earthquake ground motions. These 'snubbers' are of simple hydraulic damper design that use fluid viscosity to produce the required velocity-dependent characteristics.

There are several problems associated with using snubbers as a solution to the design problem: they are relatively expensive, they are bulky and hence present a layout problem in complex systems as each snubber provides support in one direction only, they require constant maintenance to ensure that they retain their performance specifications, and finally, even if they do behave as specified, there is no provision for significant energy absorption that could reduce pipe stresses under seismic excitation. The studies reported in this paper aim at changing the design concept and replacing the snubbers with simple energy absorbing devices made of ductile steel.

Use of Ductile Restrainers

The use of ductility as a means of controlling dynamic response is widely accepted in seismic design, and it is appropriate to study its application to the seismic design of piping systems. What complicates the problem in this case is the need to accommodate large thermal displacement. Any ductile device permanently connected to the piping has to accept the global thermal displacements of the system by elastic or ductile deformation without introducing significant self-straining forces into the piping. And under seismic conditions and at any point in the thermal cycle, the device must act as an efficient energy absorption restrainer that will reduce the pipe stresses when compared with either the unsupported or the fully supported case.

As part of this overall project, studies have already been conducted by other investigators into the effect of support ductility on the stresses in straight multi-supported pipes [1], the development of computer analysis for complex piping systems [1,2], the design of ductile restrainer devices [3], and material properties [4]. The shaking table tests are a focal point in the total program and will eventually demonstrate the feasibility of the design concept.

Shaking Table Tests

The shaking table tests are designed to parallel the computer analysis and the studies on device design, and to bring together the various aspects of the problem in a practical context. Various configurations of pipe systems will be studied, both planar and three-dimensional, and different restrainer designs and locations will be used to control dynamic response. In the first instance ductility will be restricted to the energy absorbing support devices and the pipe stresses confined within the elastic range. Later it is possible that consideration will also be given to permitting some level of yielding within the pipes themselves. In all tests, the table motions will consist of either horizontal, vertical or simultaneous horizontal and vertical components applied with increasing intensity.

The first series of tests, which is currently underway, consists of a horizontal three-sided rectangular plane loop made of 3S40 pipe filled with water. The U configuration has side dimensions of 11 ft 3 in., 17 ft 7 in., 11 ft 3 in. It is rigidly supported at the ends of the U, and vertically restrained at the two pipe corners which are unrestrained horizontally. In the first instance a single ductile restrainer will be fitted to control dynamic displacements in the horizontal direction parallel with the long 17 ft pipe axis, and the table motions will be applied in this direction. The restrainer will consist of a simple constant depth cantilever with a linear taper in width and cut from low-carbon steel plate. This design has been studied in another phase of the project [3]. Subsequently, tests will be conducted on the same pipe loop using vertical table motions and simultaneous vertical and horizontal motions, and for these tests the vertical restraints at the pipe corners will be replaced with elastic and ductile restraints in parallel at both corners. The elastic restraints will support the self-weight of the piping and center the system after the simulated earthquake; the ductile restrainers will control the vertical dynamic displacements. For seismic restraint the proposed ductile devices may have to act under a variety of possible initial conditions as related to the thermal cycle of the complete systems - in an unbiased position, in a fully biased position, and in either of these cases either before or after the maximum number of thermal cycles expected in the life of the plant. All these possibilities will be simulated in the test program and comparative studies will be designed to show any serious effects of degradation with cycling.

It is anticipated that a second test series using a three-dimensional pipe system will also be conducted in order to investigate the design, layout, and response problems associated with the development of ductile restrainers for the more complex configurations encountered in nuclear power plants.

References

1. Lee, M.C., Penzien, J., Chopra, A.K., Suzuki, S., Powell, G.H., Wilson, E.L.,Clough, R.W., and Row, D.G., "The Design of Steel Energy-Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Volume 2: The Development of Analyses for Reactor System Piping", Report No. EERC-79/08, Earthquake Engineering Research Center, University of California, Berkeley (1979).

2. Powell, G.H., Oughourlian, C., and Simmons, J., "Piping With Energy Absorbing Restrainers: Parameter Study on Small Systems" to be published by Earthquake Engineering Research Center, University of California, Berkeley (1980).

3. Kelly, J.M., Skinner, M.S., "The Design of Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Vol. 4: Review of Current Uses of Energy Absorbing Devices", Report No. UCB/EERC-79/10, Earthquake Engineering Research Center, University of California, Berkeley (1979).

4. Hartman, S.J., Zackay, V.F., and Parker, E.R., "The Design of Steel Energy-Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety, Volume 3: Evaluation of Commercial Steels", Report No. EERC-79/09, Earthquake Engineering Research Center, University of California, Berkeley (1979).

EGOR P. POPOV

University of California, Berkeley

This is a brief status report on experiments with eccentrically braced structural steel frame models subjected to quasi-static cyclic loadings simulating seismic effects. Design implications and the needs for future research are indicated. This research is co-sponsored by the National Science Foundation and the American Iron and Steel Institute.

ECCENTRICALLY BRACED STEEL FRAMES

Background

In structural steel frames diagonal braces for resisting lateral forces have been occasionally deliberately off-set from beam-column joints. Spurr [1] in his 1930 book on Wind Bracing suggests such use for architectural reasons, and it would appear that tall buildings employing braces with large eccentricities of diagonal braces at the joints were built in the New York area. A specific use of eccentric joints in spread K-braces for seismic applications has been studied by Fujimoto [2]. Experimental and analytical results on diagonally braced frame models with eccentric connections of the type shown in Fig. 1 reported by Roeder and Popov [3] aroused further interest in eccentrically connected bracing. In this study a 20-story four-bay frame of a square office building served as the prototype. Quasi-static cyclic experiments were performed on one-third scale models for a braced bay for the lower three floors of the prototype. The short segments of the beams (shear links), identified by the length e in Fig. 1, were so proportioned that during plastic deformation the webs yield in shear before reaching the moment capacity of the beam. These test frames exhibited excellent hysteretic behavior far into the inelastic range, indicating that the ductility and energy absorbing capacity of properly designed eccentrically braced frames is very good. Prompted by these findings several major buildings were designed using this system of bracing and are currently under construction in California.

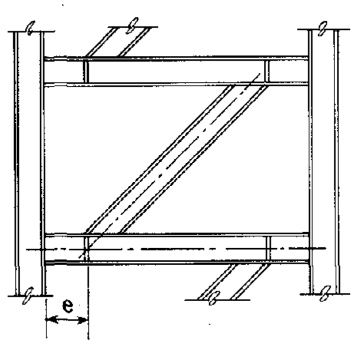


Fig. 1 Typical Diagonal Eccentric Bracing [3].

Objectives of Continuing Research

Because of the promising nature of the concept of eccentric bracing of steel frames for seismic design, the research is being continued along two directions. First, since functional (architectural) considerations may impose locating the shear links elsewhere from that shown in Fig. 1, alternative locations should be investigated. Second, since buckling caused by cyclic yielding in the webs of the shear links may occur during a severe earthquake, the current code provisions for the beam depth-to-web thickness ratios may not be sufficiently conservative. To prevent buckling of the webs vertical stiffeners along the shear link may be required in some instances. Both aspects of the problem are being studied in this investigation.

Current Frame Experiments

K-bracing offers an advantage over the diagonal bracing of the type shown in Fig. 1 by permitting large, unobstructed openings in the middle of a bay. For this reason K-bracing is frequently used in practice. By arranging such bracing with eccentricities at the joints such frames may be made to behave in a very ductile manner, and the resulting shear links would effectively dissipate energy during severe cyclic loadings.

Two models employing the eccentric K-bracing schemes illustrated diagrammatically in Fig. 2 were designed and built. As in the earlier tests, each one of these frames modeled to one-third scale a braced bay of the lower three floors of a 20-story office building. In both frames the shear links, having the lengths e, were designed to yield in shear first. For the frame shown in Fig. 2(a), to facilitate the assembly of essentially concentric joints at the bottom of the braces, small eccentricities were introduced. Note that three active shear links are required at the second floor level for the frame shown in Fig. 2(b); otherwise, the first story braces would not be protected from the possibility of backing by a shear link.

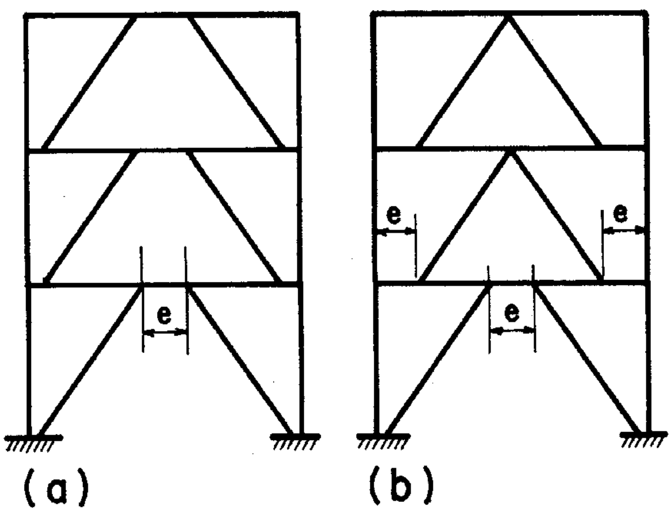


Fig. 2: Two Eccentric Bracing Schemes

To date experiments with these frames indicated two problem areas. The beams had a tendency to develop lateral torsional buckling, and the webs of the shear links buckled at moderately large lateral displacements of the frame. The observed lateral torsional buckling of the beams in large measure was due to the experimental set-up, and can be easily prevented in applications. However, the buckling of the webs in the shear links requires further investigation. It is important to note that in the earlier tests [3] where W6 x 12 beams were used, the shear links behaved well. Whereas in the new series of tests with W8 x 13 beams the webs in the shear links buckled earlier. Both beams had webs 0.23 in. (5.8mm) thick.

Design Implications

Eccentric bracing of structural steel frames provides an effective means for absorbing and dissipating energy input caused by a severe earthquake. Many schemes for locating the critical shear hinges appear possible. These hinges must be designed to yield in shear before the development of plastic end moments [4,5]. The AISC lateral bracing provisions for plastic design [6] appear to be appropriate for preventing lateral torsional buckling of the beams. However, considerable care must be exercised to prevent the webs in the shear links from buckling prematurely. Some guidance on web buckling of beams under monotonic loads is available [7]. For seismic applications for the present the possible need of stiffeners along a link can be based on the satisfactory performance of the links in the Roeder-Popov experiments [3]. This aspect of the problem is commented upon in Ref.5.

Projected Research

The two frames of the type shown in Fig. 2 are now being modified. The shear links are being reinforced with vertical stiffeners, and a better latteral support system for the beams will be provided during testing. With these changes it is believed that the frames will exhibit very good ductility.

Criteria for determining the cyclic buckling loads for the webs of the shear links must be more firmly established. For this purpose an integrated analytical and experimental approach is being pursued. The cyclic experiments on the shear links are likely to be on full-size specimens in the W18 class of sections.

References

[1] Spurr, H.V., Wind Bracing, 1st ed., McGraw-Hill, New York, 1930, p.53.

[2] Fujimoto, M., et al., "Structural Characteristics of Eccentric K-Braced Frames", Transactions, AIJ, No. 195, May 1972.

[3] Roeder, C.W., and Popov, E.P., "Eccentrically Braced Steel Frames for Earthquakes", J. Structural Division, ASCE, Vol. 104, No. ST3, March 1978.

[4] Popov, E.P., and Roeder, C.W., "Design of an Eccentrically Braced Steel Frame", AISC Engineering J., 3 rd Quarter, 1978, Vol. 15, No. 3.

[5] Popov, E.P., "Eccentric Seismic Bracing of Steel Frames", Proceedings, 7th WCEE, Istanbul, Turkey, September, 1980 (in press).

[6] Manual of Steel Construction, AISC, 7th edition, New York, 1970.

[7] Basler, K., "Strength of Plate Girders in Shear", J. Struct. Division, ASCE, Vol. 87, No. ST7 October, 1961; and Transactions, ASCE, Vol. 128, Part II, 1963.

Joseph M. Plecnik
Associate Professor
Civil Engineering Department
California State University, Long Beach

Mai G. Pham
Graduate Research Student
Civil Engineering Department
California State University, Long Beach

Han Chan
Graduate Research Student
Civil Engineering Department
California State University, Long Beach

Introduction

Earthquake related research at California State University, Long Beach has been and is currently directed towards two specific areas. First, the performance of epoxy repaired concrete components subjected to various environmental and load conditions including elevated temperatures and fire. Second, the development of design parameters and design procedures for fiberglass reinforced plastic tanks. Both of these research topics will be discussed.

Research on Concrete Repair

Extensive research has been completed or is presently in progress concerning the behavior of structures during earthquakes. However, a relatively small amount of research information is available on the behavior of earthquake damaged structures that were subsequently repaired or rehabilitated by various techniques. Therefore, a research program sponsored by the National Science Foundation has been in progress since 1974 at California State University, Long Beach dealing with repaired structures and predictions of their behavior under future earthquakes, fires and other adverse climatic conditions. Primary emphasis during current and future research programs has and will be devoted to epoxy repaired structures damaged by earthquakes and subsequently repaired with epoxy adhesives.

Past research at California State University, Long Beach and other universities and institutions indicate that damaged structures repaired properly with epoxy adhesives are restored to original design strength levels. However, strength properties of epoxy adhesives deteriorate rapidly at elevated temperatures. Therefore, experimental programs are in progress or in planning stages which will investigate the strength properties of epoxy repaired components during and after fire exposure and future earthquakes. The current research program is directed primarily towards epoxy repaired concrete shear walls and beams.

The primary objectives of the research programs are as follows:

1. Investigate the behavior and strength characteristics of epoxy repaired concrete beams and columns during fire exposure.

2. Determine the nature and extent of residual strength of epoxy repaired structural components after fire exposure under both simulated seismic loads and dead loads.

To achieve these two objectives, an experimental program has been developed beginning with small-scale specimens and culminating with standard ASTM E-119 fire tests for shear walls and beams. The experimental results will be used to develop appropriate fire ratings for epoxy repaired structures.

Results for shear walls have been completed indicating that the type and duration of fire (ASTM E-119 or the Short Duration High Intensity Fire), the thickness of the crack, the thickness of the shear wall and the presence of fire protective coatings are the primary test parameters which must be considered. References 1, 2 and 3 provide a complete summary of the test results on epoxy repaired concrete shear walls.

After completing the research program on the epoxy repaired shear walls, the research efforts are currently being directed to the behavior of epoxy repaired concrete beams subjected to elevated temperatures, fires and subsequent earthquakes. This experimental program will attempt to study a variety of parameters including (a) the feasibility of epoxy repair techniques for various types of damaged beams, (b) the temperature properties of epoxy-grout, (c) the characteristics of epoxy rebonded steel reinforcement under elevated temperatures and, (d) the effectiveness of fire surface coatings for epoxy repaired concrete beams. Upon completion of this research on epoxy repaired beams, the effects of elevated temperatures and fire on epoxy repaired concrete columns will be investigated.

Earthquake Research on Fiberglass Tanks

The second area of earthquake related research at California State University, Long Beach deals with the design procedures and strength properties of vertifal fiberglass tanks. This research program has been in progress since 1976 and has been sponsored by Dart Fiberglass Division, Proform Inc., and Tankinetics, Inc.

In this fiberglass tank research program, the topics which have been and are currently being considered include the following:

1. Anisotropic material properties for more than 1,000 different wall thicknesses and laminar constructions were developed.

2. More than 800 finite element models for seismic lateral loadings and slushing were developed for the various tank and laminar constructions.

3. Design procedures for filament wound fiberglass tanks were developed taking into consideration the Uniform Building Code and ASTM D3299.

4. Anchor bolts and lugs were designed for optimum structural performance and cost.

5. Experimental investigations were performed on small-scale specimens and full-scale tanks using static and simulated seismic loads.

6. Currently, tests are being conducted on the performance of fiberglass tanks during various types of fire exposures and flame spread characteristics.

References

1. J. M. Plecnik, B. Bresler, J. D. Cunningham, R. Iding, "Temperature Effects on Epoxy Adhesives", Journal of Structural Division, ASCE, Vol. 106, No. ST1, January 1980, pp. 99-113.

2. J. M. Plecnik, R. B. Williamson, M. G. Pham, W. Whitman, "Strength Properties of Epoxy Repaired Structural Components During and After Fire Exposure", to be presented at the 7th World Conference on Earthquake Engineering, Istanbul, Turkey, Sept. 1980.

3. J. M. Plecnik, M. G. Pham, H. C. Chan, "Final Report to NSF on Fire Research of Epoxy Repaired Concrete Shear Walls", California State University, Structures Lab. Report #SL80-5-1, 1980.

GARY C. HART

University of California, Los Angeles

This paper summerizes current research at the University of California at Los Angeles sponsored by the National Science Foundation in the areas of Building Full Scale Earthquake and Ambient Response Measurement and Data Analysis, and System Identification.

Building Full Scale Earthquake and Ambient Instrumentation

The UCLA Full Scale Earthquake and Wind Laboratory was created in the spring of 1975. The formation of this laboratory was the logical organization result of past research interests which existed at UCLA for many years prior to 1975. Work prior to that date was primarily supervised by R.B. Matthiesen and the author. NSF funding in 1975 for an indepth instrumentation of the high rise buildings in the Century City area of Los Angeles was the corner stone in the laboratory foundation. Since the formation of the laboratory the following buildings have been instrumental: (1) Twin 43 - story Steel Frame Theme Buildings in Century City (24 accelerometers). (2) 25 - story Steel Frame Century City North Building (16 accelerometers). (3) 7 story Shear Wall UCLA LIfe Science Building (32 accelerometers). The above buildings record earthquake and ambient response, transmitted by telephone and radio, on a 128 Channel Kinemetrics DD51105 Analog to Digital Recorder. Response sensors are Kinemetrics FBA-1 accelerometers. The replacement cost of instrumentation in these three buildings is approximately $150,000.

The laboratory has a commitment to providing assistance to the State of California strong motion program. This assistance has been in selection of buildings for instrumentation, selection of instrument locations and data analysis. The laboratory personnel performed this assistance on two buildings of special note. One is the 3 story shear wall North Hall building on the UCSB campus. Harmonic vibration tests were performed on this building before and after a major structural strengthening. In addition, the earthquake response records obtained in this building during the August, 1978, Santa Barbara earthquake were analyzed. The second building of note was the El Centro County Services building. This building is of considerable future interest to earhtquake engineers.

Building Full Scale Earthquake and Ambient Response

Ambient response measurements can be obtained in a planned manner. This has been done for the above noted buildings.

Earthquake response measurements are beyond one predictable control. However, in addition to the North Hall and El Centro County Services Building earthquake response records, earthquake response of the Life Science building was measured during the 1979 Malibu earthquake. These records are presently under analysis.

What are the Objectives?

Besides obtaining full scale real world building response measurements what are the basic objectives of the program? The items which are believed to require measurement insight and therefore are at the current foundation of our research objectives are: (1) What is the actual measured twisting motion of building floors and foundation? (2) What is the actual measured rocking or overturning of building foundation? (3) Are seismic joints working? (4) What are actual measured intro-story motions? (5) Can floor acceleration response records obtained from periodically obtained ambient response tests be used to detect structural damage or a loss in building strength? We have planned building instrumentation arrays in an attempt to obtain measurement data which will help to answer these questions.

System Identification

Full Scale building measurements are most valuable if this full scale real world laboratory test data can be used to assist in the verification of analytical models which can then be used for the design of new buildings and the evaluation of existing buildings. System Identification research must provide help in this area. Three completed UCLA Ph.D. theses funded by NSF grants have made a small step toward providing this help.

DIXON REA

University of California, Los Angeles

The inelastic deformations that earthquake motions can produce in structures are being investigated by means of experiments conducted with a high-performance shaking table. In particular, the maximum and permanent displacements produced by various intensities of the N21E component of the Taft (1952) earthquake are being established. The objectives of the experiments are to gain a better understanding of the structural mechanics involved in the development of inelastic deformations during earthquakes and to accumulate experimental data that can be used for checking the accuracy of existing computer programs for nonlinear dynamic analysis of structures. Experiments are being conducted on three types of structures:

(1) Steel frame structures
(2) Coupled reinforced concrete shear walls
(3) Reinforced earth walls.

Steel Frame Structures

The steel frame structures are designed to reproduce the overall behavior of three story shear-type buildings in which the flexural stiffnesses of the beams are large compared to those of the columns. The floors consist of 2 in by 1/2 in rectangular steel bars bolted together to form 12 in by 24 in rectangular frames. The columns have 1/2 in by 1/4 in rectangular cross-sections and clear heights of 8 in. They are machined from bars of hot-rolled A36 steel and assembled so bending takes place about their weaker axes. Each structure was subjected to several levels of intensity of a motion derived from the Taft (1952) earthquake record. The lowest level of intensity was chosen so the response of the structure would remain within or barely outside the linear range of behavior. The highest levels of intensity were chosen to produce inelastic, including permanent, deformations. The structures were subjected to motions having acceleration and velocity peaks up to 5 g and 50 in/sec respectively. The results from experiments on twenty structures have been described in reference (1). The experimental data is being used to check the accuracy of the computer program DRAIN-2D(2).

Coupled Reinforced Concrete Shear Walls

The coupled reinforced concrete shear walls consist of two in-plane shear walls connected by five beams. The overall dimensions of the walls are 9 in wide, 30 in high and 1 in deep. The individual shear walls are 3 in wide, and they are reinforced with a total of 10 longitudinal bars of No 4-40 threaded steel rods. The 3 in long by 1-1/2 in deep coupling beams are reinforced with four No 4-40 threaded steel rods that have been annealed to reduce the yield stress of the steel to about 45 ksi. Shear reinforcement is provided by .05 in diameter black annealed steel wire. The walls will be tested in pairs, 24 in apart, but connected at each floor level by two steel bars weighing 100 lb each. The natural frequency of the resulting structure will be about 20 Hz, and it will be subjected to a time-scaled version of the Taft (1952) earthquake record.

The first pair of shear walls have been constructed, and the shaking table experiments are scheduled for Spring 1980.

Reinforced Earth Walls

The reinforced earth walls were constructed using 1/4 in by 3 in by 30 in plexiglas plates as face elements, 1/2 in wide strips of mylar tape as reinforcing ties, and a fine sand with an internal angle of friction of about 35^o as backfill. The horizontal and vertical spacings between ties in the backfill was 6 in and 1-1/2 in respectively. The backfill was placed uniformly by letting the sand fall through a spreader box from a height of 18 in. This procedure results in a backfill that has an average density in place of 103 lb/ft^3 or a relative density of 85%. Walls with heights of 12 in, 18 in, and 24 in and tie lengths from 10 in to 30 in have been subjected to motions derived from the Taft (1952) earthquake record. Some results from tests on 18 in high walls have been reported in reference (3). It is planned to use the experimental results in developing a computer program for calculating the magnitudes of earthquake-induced permanent deformations in reinforced earth walls.

References

(1) Dixon Rea and Alvar M. Kabe, "Earthquake-Induced Permanent Displacements in Small Shear-Type Steel Structures," to be presented at the 7th WCEE, Istanbul, Turkey, September 1980.

(2) A.E. Kanaan and G.H. Powell, "DRAIN-2D A General Purpose Computer Program for Dynamic Analysis of Inelastic Plane Structures," Report No EERC 73-22, University of California, Berkeley, August 1975.

(3) Dixon Rea and William E. Wolfe, "Earthquake-Induced Permanent Displacements in Model Reinforced Earth Walls," to be presented at the 7th WCEE, Istanbul, Turkey, September 1980.

BRUCE M. DOUGLAS

Civil Engineering Department
University of Nevada
Reno, Nevada 89557

Experimental Dynamic Response of Highway Bridges

A program to experimentally identify the dynamic characteristics of highway bridges (frequencies, mode shapes, and damping) was begun in 1974. The experimental transverse dynamic properties were obtained by the method of quick-release pullback testing where multiple crawler tractors were used to laterally deform the structure. Vertical motions were studied by using excitations produced by random truck traffic, and by excitations caused by dropping the rear wheels of a loaded truck off small ramps.

In the initial study a six span composite girder bridge was examined in detail [1]. Under the current program experimental data has been collected for two additional bridges. One is a reinforced concrete box girder structure and the other is a variable depth skewed composite girder bridge. In addition, a limited amount of ambient vibration data (suitable for frequency identification only) was obtained for these structures. The ambient vibration data will be used to help establish the extent to which the test results depend upon the amplitudes of vibration.

The experimentally determined damping ratios, mode shapes, and natural frequencies were then used in conjunction with a detailed lumped mass analytical model to establish the appropriate structural modelling assumptions. The relevant earthquake response behavior of the structure is developed by using these experimentally calibrated analytical models.

A. Concrete Box Girder Interchange

This bridge is a five-span 400 foot long reinforced concrete girder bridge supported by four single column piers and elastomeric bearing pads at the abutments. The structure is supported on piles because the soil profile consists of a layer of soft clay over a layer of stiff clay on dense sand and gravel.

Four transverse and three vertical mode shapes were identified for this structure along with its natural frequencies. From these dynamic characteristics it was possible to infer the important structural properties of the system: (a) the stiffness of the elastomeric bearing pads due to short duration loads, (b) the effective moments of inertia of the individual spans for both vertical and transverse motions, (c) appropriate transverse shear deflection factor for the box girder and (d) the individual in-situ lateral stiffness of the pile foundations.

Preliminary conclusions are [2]: (a) the elastomeric bearing pads are many times stiffer in resisting short duration loads than the long- term thermal strains. (b) the effective transverse moments of inertia and shear deflection factors are consistent with the extent of cracking in the box section caused by vertical loads and (c) the lateral stiffness of the pile foundations is a significant factor in determining the lateral earthquake response of the bridge. The seismic response of this system will be compared to the results from the design criteria, and to the current AASHTO requirements.

B. Variable Depth Skewed Composite Girder Bridge.

This five girder bridge is a three span 400 foot long continuous beam railroad overcrossing with a 54^{o} skew on I-80 at Deeth, Nevada. A complex finite element space frame model was developed to explain the relatively complicated experimental data obtained from this bridge.

Preliminary results [3] indicate that the transverse bracing frames, and the presence of a large sidewalk-barrier rail detail on the outside girders, strongly influence the response of the system. In addition, a simple single girder model of the system is quite inadequate to explain the dynamic data. The behavior of this system under earthquake loads will be examined in detail.

Acknowledgements

This project has been supported by the Federal Highway Administration, the National Science Foundation and the Nevada State Department of Transportation.

References

1. Douglas, Bruce M. (1976) Quick release pullback testing and analytical seismic analysis of a six span composite girder bridge, Report No. FHWA-RD-76-173, Federal Highway Administration, Offices of Research and Development, Washington, D.C., 73 pp.

2. Douglas, Bruce M. and Monte Gordon (1980) Experimental and analytical dynamic response study of a reinforced concrete box girder bridge, 75th Annual Meeting Seis. Soc. of Amer., Abstract with program - accepted for presentation.

3. Douglas, Bruce M. and Charles D. Drown (1980) Dynamic characteristics of a variable depth skewed composite girder bridge, 75th Annual Meeting Seis. Soc. of Amer., Abstract with program - accepted for presentation.

ANSHEL J. SCHIFF

Purdue University

The purpose of the National Science Foundation supported research is to improve the earthquake response of electric power substations. The 1971 San Fernando and 1978 Sendai, Japan earthquakes demonstrated that substations and, in particular, higher voltage equipment are vulnerable to severe earthquake damage. This research has three main thrusts. First to develop a draft design guide, develop educational material to be used by utilities primarily outside of California where little is now done to improve seismic response of substations, and perform research to investigate potential problem areas in substations.

Draft Design Guide

A draft of a substation design guide is to be prepared and submitted to the Electric Power and Communications Committee, Technical Council for Lifeline Earthquake Engineering, American Society of Civil Engineers. The Committee will use this as a working draft to prepare a censensus document. As part of the design guide an annotated Bibliography (1) has been prepared and submitted to ASCE for publication. The Bibliography contains 485 items and is cross referenced so that information on different types of equipment can be identified, such as circuit breakers, transformers, cooling towers, piping, etc. or by type of work such as analysis, damage reports, or tests. The power systems part of the Bibliography is 80 pages in length.

Improving Substation Design in Regions of Low Seismic Awareness

Outside of California very little has been done to improve the earthquake resistance of substations. The techniques are available and the cost of their implementation on new facilities often is less than those associated with current practice. Thus, if improved earthquake resistance is to be achieved without mandatory regulations, educational material must be prepared which clearly shows the problems and low cost methods for reducing damage. The first stage of this effort, a picture book which illustrates power system damage and low cost methods to improve earthquake resistance, is complete (2) and is now being published. Several sample designs for combined loads (ice, wind, short circuit, and seismic) on substation equipment are being developed to illustrate those features which affect earthquake resistance.

Special Problems of Earthquake Resistance of Substations

Two additional analysis/experimental programs are in progress. The first is developing a finite element model of a 765 kV circuit breaker using special methods for evaluating the reliability of ceramic members (3). The San Fernando earthquake and subsequent analyses have shown that high voltage circuit breakers are very vulnerable to earthquake damage. To date, the highest voltage circuit breakers which have been subjected to detailed dynamic analysis and testing have been of the 500 kV class. Permission has been obtained to test a 765 kV circuit breaker under low level excitation. Detailed analysis is now in progress.

Some of the damage from the Sendai, Japan earthquake indicated that the dynamic response of long flexible primary conductors or busses induced equipment failures. In addition, there are no standards or guides as to the tension which should be applied when installing flexible busses. Finite element analyses are being used to investigate these problems.

Included in the References are papers prepared with NSF support.

References

1. Schiff, A. J., "Annotated Bibliography of Lifeline Earthquake Engineering, Power Systems Section," to be published by ASCE.

2. Schiff, A. J., "Pictures of Earthquake Damage to Power Systems and Cost Effective Methods to Reduce Seismic Failures of Electric Power Equipment," School of Mechanical Engineering, Center for Earthquake Engineering and Ground Motion Studies, Purdue University, West Lafayette, Indiana.

3. Schiff, A. J., Torres, R. E. and Yao, J. T. P., "Evaluating the Seismic Response of Electrical Equipment Containing Ceramic Structure Members," *International Journal of Earthquake Engineering and Structural Dynamics*, Vol. 7, January 1979, pp. 85-98.

4. Schiff, A. J., "Seismic Emergency Operations of Power Systems," *Journal of the Technical Councils of ASCE*, TC1, November 1978, pp. 1-11.

5. Schiff, A. J., Newsom, D. E., and Torres, R. E., "Fragility of Electrical Power Equipment," *Journal of the Technical Councils of ASCE*, TC2, ASCE, December 1979, pp. 451-465.

6. Schiff, A. J., "Affecting Improved Power System Seismic Resistance," *Journal of the Technical Councils of ASCE*, TC2, ASCE, December 1979, pp. 337-341.

ANSHEL J. SCHIFF
HENRY T. Y. YANG

Purdue University

The San Fernando Earthquakes demonstrated the vulnerability of elevators to earthquakes. In the Los Angeles area there was little structural damage to high rise buildings from the earthquake. Yet 640 elevator counterweights, mostly in Los Angeles, came out of their guide rails. In this condition, should the counterweights and elevator cab attempt to pass each other, severe damage will result and create a severe life-safety hazard. The earthquake hazard of elevators can, by and large, be eliminated with current technology. The difficulty is that the cost of these solutions is so great that there would be tremendous resistance to adopting such a code in many parts of the country where elevator seismic performance should be improved. This report describes the research directed at improving the earthquake response of elevators in a cost-effective manner.

Modeling Counterweight-Rail System

The counterweight-rail system consists of a stack of about 20 weights constrained to a frame (the counterweight frame). While the frame is designed to keep the weights within it, the weights are free to move from one to several inches within the frame. The frame has guides at each of its corners which keeps it within the guide rails. Figure 1 shows a schematic of the system. The stiffness of the frame and the rail are about the same. The counterweights and frame typically weigh about 7,000 pounds. The seismic response of the structure primarily causes rectilinear motion in and perpendicular to the plane of the paper of Frame 1. There may also be rotating about the horizontal and vertical axis. Motion, particularly when the counterweights are between floors can be quite nonlinear. Nonlinearities arise from the gaps between the weights and the counterweight frame and the counterweight frame and the rails and changes in system stiffness as the counterweight frame comes in contact with the rails.

At the present time a simplified physical model has been constructed and tested. Test results are being evaluated to identify different types of response due to system nonlinearity. These results will form the basis for validating nonlinear finite element models. The finite element models will then be modified to determine the influence of various system natural frequencies, spacing between elements and the introduction of dissipative materials into the design. The results of these studies will indicate certain design parameter combinations to be avoided and the effectiveness of design modifications.

Modeling Elevator Rope Dynamics

Finite element models to evaluate the dynamic response of elevator ropes are being made. Rope dynamics are a problem for both seismic loads and wind loads on structures. Simple passive means for dissipating or converting the energy in the ropes to a nondestructive form.

Influence of Structural Response on Elevators

The seismic dynamic response which the elevator system experiences, particularly higher in the structure is narrow band excitation corresponding to the lower structural modes of vibration. Aside from the frequency, which is primarily influenced by the height of the structure, the structural system used to resist lateral forces may have a strong influence on elevator response. Clearly, in a core type sytsem in which the elevator shaft serves as the main lateral load resisting element, the motion within the core would be much less than that observed at the periphery of the structure particularly if nonsymmetry induces tortional responses.

In this phase of the research ambient response data is to be gathered from several structures which characterize different building systems. The influence of the structural system on the elevators will then be assessed for each system.

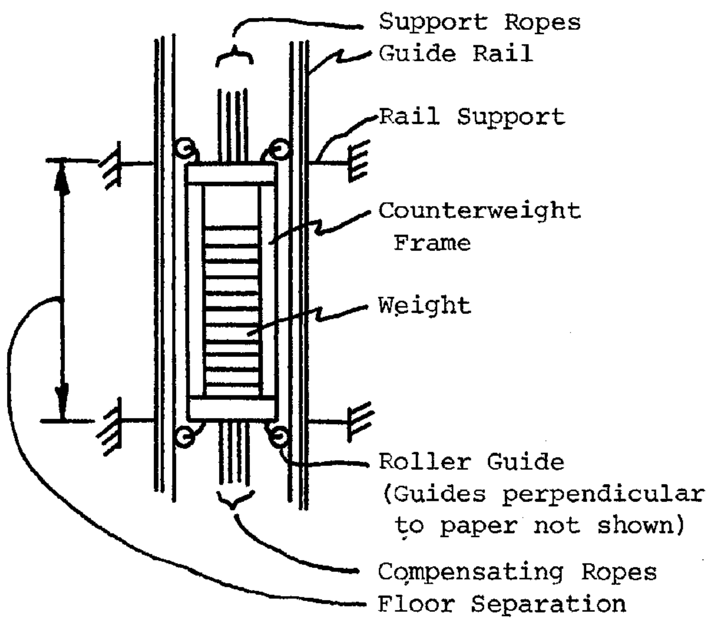


FIGURE 1

HELMUT KRAWINKLER

Stanford University

Two projects are described in this research summary. The first project has recently been completed while the second project is in an early state of progress. Both projects are financially supported by the Earthquake Hazards Mitigation Program of the National Science Foundation.

Applications of Model Analysis in Earthquake Engineering

This project is a continuation of previously reported work on scale modeling and testing of structures on small shake tables. The last phase was concerned primarily with the simulation of material properties at model scales, with specific model case studies and with the application of model analysis to different aspects of earthquake engineering research.

Adequate simulation of material properties has been found to be the most important aspect of model research, particularly under dynamic excitations. Materials for modeling of steel structures (structural steel and copper alloy 510) and reinforced concrete structures (wire-reinforced microconcrete) were investigated under low and high strain rates and were found to be adequate model materials for many applications. A comprehensive set of material data has been assembled for direct use in model studies, and systematic material testing procedures have been developed for the investigation of alternative model materials.

The adequacy of the simulation of prototype response has been studied in a series of dynamic tests on models for which prototype test data were available. The correlation between model and prototype response was good to excellent, depending on the type of structure. Whenever discrepancies in the response were observed, the causes were identified and evaluated to assess the limitations of model research in earthquake engineering.

Sample test results of model case studies are presented in Figs. 1 and 2. Figure 1 shows a comparison of the localized inelastic response (strain history in a joint panel zone) of a prototype and 1:6 scale model of a three story steel frame structure tested on shake tables. Figure 2a shows load-deflection hysteresis loops of a reinforced concrete cantilever beam with high shear. The solid lines represent the prototype response while the dashed lines represent the response of a 1:15 scale model. The effects of different strain rates on the load-deflection behavior of reinforced concrete beams are illustrated in Fig. 2b which shows the results of 1:15 model tests carried out with frequencies of 0.0025, 2 and 10 Hz.

The research has demonstrated that model analysis can be used in many cases to obtain quantitative information on the seismic response of complex structures which cannot be analyzed confidently by conventional techniques. Methodologies for model testing and response evaluation have been developed in the project and the possibilities as well as limitations of model research in earthquake engineering have been investigated.

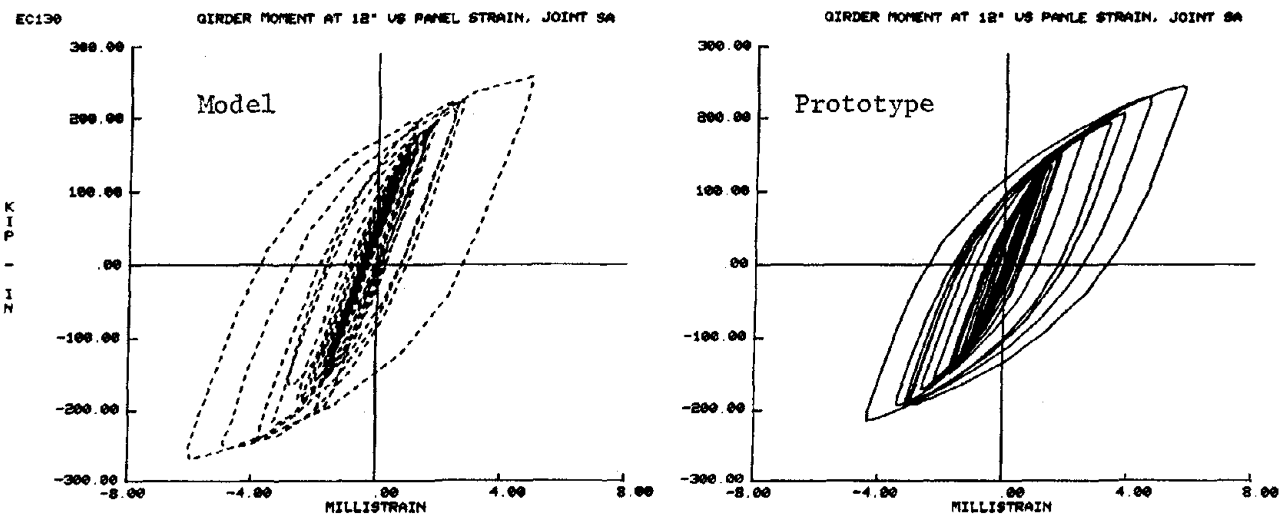
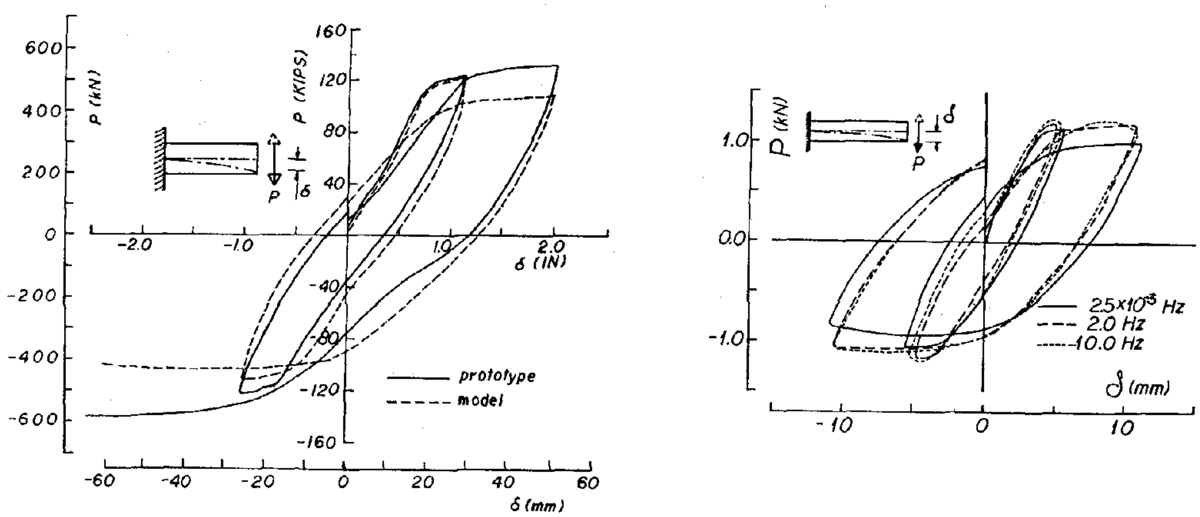


Fig. 1 Girder Moment vs. Panel Strain in Joint Panel Zone



(a)

(b)

Fig. 2 Load-Displacement Response of Reinforced Concrete Model Beams

Experimental Methods for Determining the Seismic Behavior of Structural Components

This research is concerned with the development of experimental procedures for determining the seismic response characteristics of components of steel structures. From this study a set of recommendations will be developed for the type of experimental work that is needed to produce reliable information which can serve as a basis for the development of rational design criteria.

Specifically, it is planned to identify the types of test specimens and experiments needed to evaluate the performance of components. The low cycle fatigue characteristics of components will be studied in detail in order to develop recommendations for cyclic loading histories and testing procedures. The parameters will be identified that are needed to describe the behavior of the component as part of a structural system which may be subjected to one or several seismic events of various intensities.

Emphasis will be placed on developing low cycle fatigue and fracture models for components under random loading histories. This should permit a more rational evaluation of the reliability of structural components and connections under seismic excitations. Damage accumulation models will be developed utilizing material fatigue properties as well as experimental data from a series of cyclic loading tests of structural components. The approach to the reliability evaluation of connections will be based on concepts of probabilistic elastic-plastic fracture mechanics, utilizing the ΔJ integral to model crack propagation.

This research originated from a need for a more systematic approach to experimentation and presentation of data in earthquake related laboratory investigations of the performance of structures. The specific needs towards which the proposed research is directed are (1) identify the objectives of experimental studies, (2) develop guidelines for the selection of test specimens, testing procedures, and presentation of experimental data, (3) establish guidelines for a consistent user oriented evaluation of experimental data, and (4) aid in an evaluation, and, if necessary, revision of present national standards concerned with relevant testing procedures.

H. E. LINDBERG, G. R. ABRAHAMSON, and J. R. BRUCE

SRI International

We have completed the second year of an NSF-sponsored program to develop a technique that uses explosives to simulate strong level, earthquake-like ground motion. The long range objective is in-situ testing of soil-structure interaction and of large structures with complex internal equipment systems. The technique will be applicable to buildings, nuclear reactors, water and oil tanks, pipelines, power distribution systems, dams, bridges and tunnels.

The technique produces ground motion by simultaneous firing of a planar array of vertical line sources as sketched in Figure 1. Controlled release of the resulting high-pressure explosion products from a steel canister into a surrounding rubber bladder within each source allows controlled pressurization of the surrounding soil. In this way, both the amplitude and frequency content are controlled at levels suitable for testing with the array close to the test structure. This opens the possibility of in-situ testing at high levels of ground motion with a minimum of explosive and little disturbance to the surroundings. Only spent gases are released to the atmosphere, so tests in populated areas are possible. The array can be reused indefinitely by simply inserting new charges into the canisters. Charge weights are hundreds of pounds rather than hundreds of tons as in comparable uncontained arrays.

Figure 1 summarizes key results from the largest charge fired last year (6.2 pounds in the total array) and gives plans for this year. The 6.2 pounds translates into 120 pounds in the 40 x 80 foot array to be tested this year. The 120 pounds is three orders of magnitude smaller than the 140,000 pounds of explosive fired by the University of New Mexico in uncontained array tests for EPRI. Motion from the contained array is comparable to that in the much larger uncontained array, and models of the same size as in the EPRI tests are planned.

Seven array tests were performed this year and are summarized in Figure 2 in a comparison with theoretical predictions. These tests demonstrated that the array is reusable for many tests, that tests with the same amount of explosive are repeatable, and that tests with increased amounts of explosive give a systematic increase in motion amplitude. The theory is an elastic-plastic calculation based on measured properties of "undisturbed" soil samples taken from the site. The key result of both theory and experiment is that energy coupling between the array and soil increases abruptly beyond a critical source pressure at which the entire soil mass between sources is driven into the plastic range.

In application testing, the array could be fired at the rate of a few tests per week for an indefinite period with little or no repair between tests. This year's larger sources are designed so they can be removed and used for testing at other sites if desired. In tests with the larger array, a 30 x 30 foot test area will be available for other experimenters on a first-come basis. Interested parties should contact the authors at SRI or Dr. M. P. Gaus at NSF.

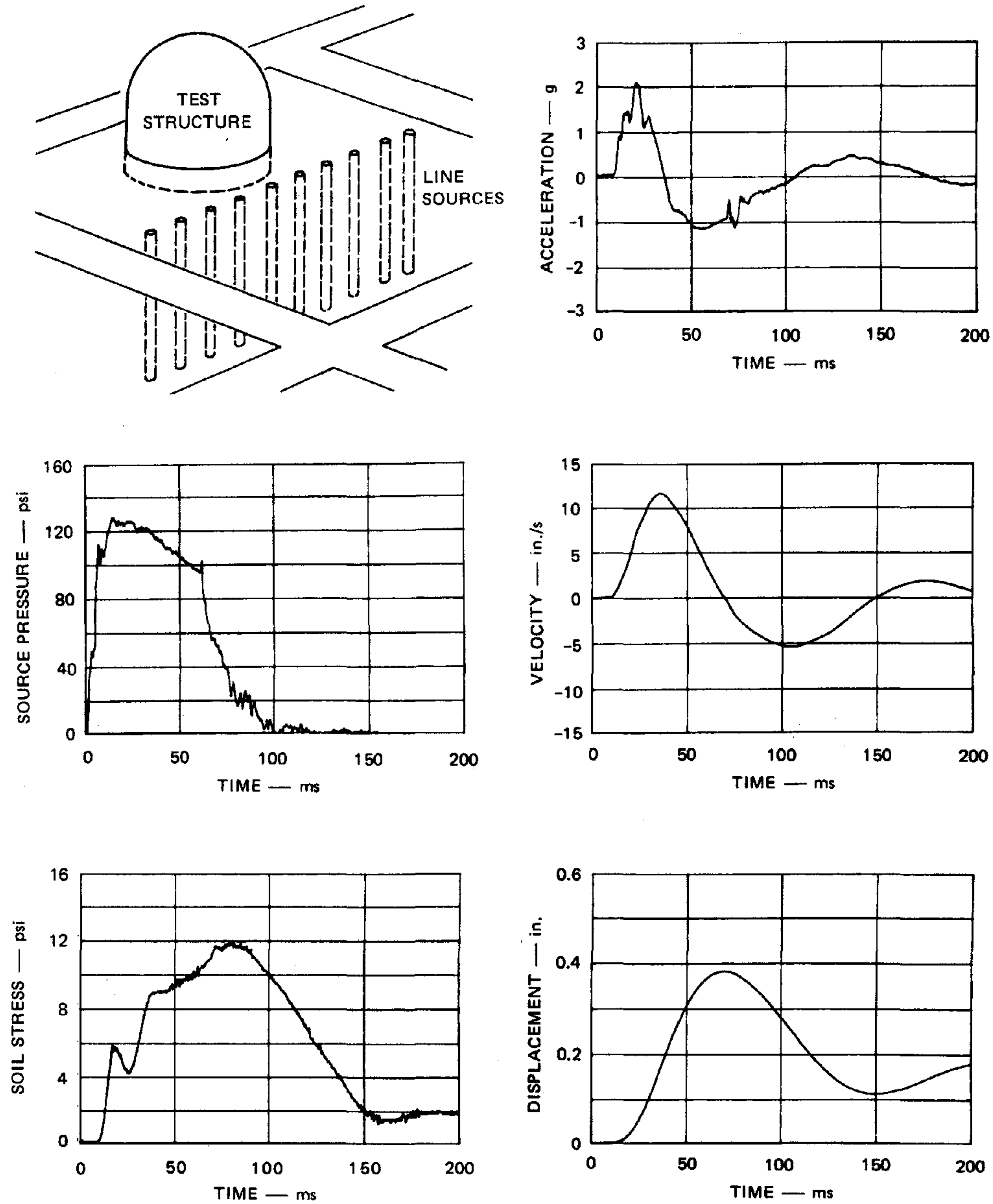


FIGURE 1 SCHEMATIC OF LINE SOURCE ARRAY, AND SOIL STRESS AND MOTION PRODUCED IN THE STRUCTURE TEST AREA BY 1/3-SCALE ARRAY TESTED LAST YEAR

This array is 15 feet deep and 30 feet wide. Tests this year with a 40 x 80 foot array will produce similiar motion in two 30 x 30 foot test areas, one on each side of the array. Time of motion will be expanded by a factor of 3 and corresponding peak motions will be 0.6 g acceleration, 12 in./sec velocity, and 1.2 inch displacement. Larger and smaller values and other frequencies will be produced by adjusting the source pressure and duration and by using multiple explosions in each source.

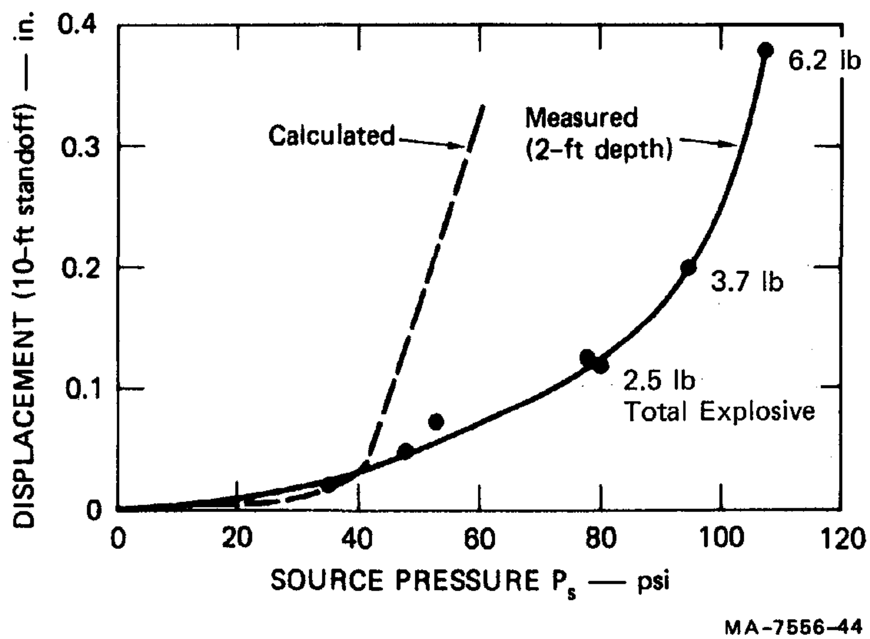


FIGURE 2 CALCULATED AND MEASURED RELATION BETWEEN SOURCE PRESSURE AND SOIL DISPLACEMENT

FIRDAUS E. UDWADIA

University of Southern California

This is a brief summary of some of the research which is being conducted at the University of Southern California in the area of identification and optimization.

1. Study of Uniqueness Problems in System Identification [1,2]

An investigation has been carried out into the nature of nonuniqueness in parametric modeling of building structures. Using the simple model of a damped shear beam, the discrete stiffness and damping parameters have been shown to be uniquely identifiable if time history records are obtained at the lowest story. The analysis further goes on to show that nonuniqueness problems may have, from an engineering standpoint, a significant practical impact on the predicted values of base shear forces.

2. System Identification for Large Systems through Optimal Control Formulations [3,4]

A new method of system identification using optimal control strategies has been developed. The method shows promise in dealing with large dynamic systems, in that it updates the parameter guesses in a systematic and automatic manner with computational efficiency which far surpasses that available in the usual identification procedures. For large systems where a large number of parameters need to be identified, this technique appears to work well.

3. Optimal Sensor Locations for Structural Identification [5]

The research in this area addresses the following question: "Given M sensors, where should they be located so that the records obtained from those locations yield the "best" estimates of the system properties?" The optimal sensor location problem can be viewed at in terms of: (1) a class of models, (2) a class of parameters (functionals) to be identified, (3) the class of inputs to be used for identification, and (4) the class of estimators used for the identification.

The line of reasoning followed by us is to uncouple the identification aspects from the optimization aspects of the problem. This leads to results which are independent of the estimator used.

A general methodology [5] has been developed for optimal sensor locations in building structures and it appears to give results which bear out the answers available from direct computations.

4. Methodology for Locating Strong Motion Arrays [6]

Investigation of a methodology for locating strong motion accelerographs in a seismically active region is currently being undertaken.

Starting with the probability density of earthquakes in a given region, the research attempts, within the framework of optimization theory, to formulate the following two questions: (1) given N accelerographs, where should they be located in a seismically active zone, and (2) having fixed these N accelerographs, where should the next M be located?

Three different cost functions are presented. Some closed form solutions are illustrated for problems when N and M are small. For larger arrays, numerical optimization is resorted to.

To demonstrate the methodology, a region with J faults, with given spatial locations is selected. An efficient algorithm for optimization is utilized and the technique illustrated. Good agreement with closed form solutions obtained in some simple cases is indicated. Specific application of the method to the locationing of twenty strong motion instruments in a seismically active area has been carried out, and the patterns of sensor location for each of the cost functions, illustrated.

5. Response of Mechanical Equipment to Earthquake Excitation

The major objectives of this comprehensive analytical and experimental study are to:

a) Investigate the effects of nonlinear system modeling and scaling on the ability to predict the structural response characteristics of complex mechanical components.
b) Develop simplified nonlinear models for certain types of mechanical equipment.
c) Develop design curves for preliminary design of systems with geometric and material nonlinearities under transient dynamic loads.
d) Develop probabilistic response spectra for equipment components under earthquake excitation.

6. System Identification Techniques

Analytical and experimental studies are underway to develop efficient parametric and nonparametric identification techniques for use with nonlinear structural dynamic systems. Techniques for parametric and nonparametric identification of building structural systems have been developed and their applicability demonstrated by using real data obtained from the response of full-scale structures to wind and earthquake loads.

References

1. Udwadia, F.E., P.C. Shah, and D.K. Sharma, "Uniqueness of Damping and Stiffness Distributions in the Identification of Soil and Structural Systems," ASME Journal of Appl. Mech., Vol. 45, 1978, pp. 181-187.

2. Udwadia, F.E. and D.K. Sharma, "Some Uniqueness Results Related to Builing Structural Identification," SIAM Journal of Appl. Math., Vol. 24, No. 1, 1978.

3. Udwadia, F.E. and P.C. Shah, "Identification of Structures through

Records Obtained during Strong Ground Shaking," Trans. ASME, Series B, Vol. 98, No. 4, 1976.

4. P.C. Shah, "Models and Identification Algorithm for Distributed Parameter Systems," Proc. of Conf. on Applications of Computer Methods in Engineering, Univ. of So. Calif., Vol. 1, 1978, pp. 613-624.

5. Udwadia, F.E. and P.C. Shah, "A Methodology for Optimal Sensor Locations for Identification of Dynamic Systems," ASME Journal of Appl. Mech., Vol. 45, 1978, pp. 188-196.

6. Udwadia, F.E. and H. Miura, "A Methodology for Locating Strong Motion Arrays," accepted for publication in Int'l. Journ. of Earthquake Engg. and Structural Dynamics.

JAMES O. JIRSA

The University of Texas at Austin

Virtually all previous experimental work on the behavior of columns has been concentrated on unidirectional lateral loads and constant axial loads (generally compressive). However, seismic motions can occur in any horizontal direction in a structure and may be accompanied by variable axial forces on the columns (tension or compression). A series of columns and beam-column joints is being tested to determine the influence of bidirectional lateral deformations and varying axial forces on the behavior of reinforced concrete frame elements.

Column Tests

Thirty specimens simulating a short column between stiff floors have been tested. The columns have a cross section of 30×30 cm and a length of 91 cm. The longitudinal reinforcement consists of eight 19 mm bars with 90° hooks anchored in the end blocks. Transverse reinforcement is fabricated from 6 mm deformed bars. The specimens are subjected to a number of load histories, as discussed below. In each case the lateral deformations are applied to a given level for three reversals and then the deformation is increased or the deformation path changed.

Series 1, Lateral Load Histories (10 Tests). No axial load, constant geometry, with the following lateral deformation paths: unidirectional; unidirectional with constant deflection in one direction; bidirectional, previous loading in orthogonal direction, 3 cycles to selected level; bidirectional, alternate directions; skewed along a 45° axis (uni- or bidirectional); Z-pattern, quadrants 1 and 3; and square.

Series 2, Axial Load Variations (10 Tests). Constant compressive or constant tensile axial loads with unidirectional or bidirectional lateral deformation paths and alternating tensile and compressive axial loads under unidirectional or bidirectional lateral loads.

Series 3, Reinforcement Variations (10 Tests). The ratio of shear capacity to flexural capacity is varied in order to obtain a wide range of member behavior. The shear to flexure capacity is varied by altering the amounts of longitudinal and transverse reinforcement relative to one another.

Series 4, Cross Section Variations (8 Tests). In the previous tests the column section is square and symmetrical. A series of tests will be conducted in 1980 to determine the response of rectangular, unsymmetrical sections under varying lateral load histories.

Beam-Column Joint Tests

The specimen represents an interior beam-column joint of a frame without a slab. The tests are intended to demonstrate joint distress and the specimen is designed so that joint strength and stiffness are critical in subassembly behavior. The column is 38 cm square and 3.8 m high. The beams in both directions are 33×46 cm. Axial load applied to the column is held at a constant level of 1335 kN compression during all tests.

Seven tests have been conducted to date. The variables are loading history (unidirectional vs bidirectional lateral loads), beam longitudinal reinforcement, and joint transverse reinforcement. A series of tests will be conducted during 1980 in which the following variables are considered: level of axial load, inclusion of floor slab, and beam geometry.

References

Maruyama, K., "Shear Behavior of Reinforced Concrete Members under Bidirectional Reversed Lateral Loading," unpublished Ph.D. dissertation, The University of Texas at Austin, May 1979.

Ramirez, H., "Effect of Axial Loads on the Behavior of Reinforced Concrete Short Columns under Cyclic Lateral Deformations," unpublished Ph.D. dissertation, The University of Texas at Austin, May 1979.

Woodward, K. A., "Behavior Classification of Short Reinforced Concrete Columns Subjected to Cyclic Deformations," unpublished Ph.D. dissertation, The University of Texas at Austin, May 1980.

Longwell, J. E., "A Comparative Study of Biaxially Loaded Reinforced Concrete Beam-Column Joints," unpublished Master's thesis, The University of Texas at Austin, May 1980.

R. E. KLINGNER

University of Texas at Austin

This paper summarizes current research being conducted by the author in the areas of Anchorage Requirements for Deformed Rebars in Grouted Masonry and Shear Resistance of Short Anchor Bolts under Reversed Cyclic Loading.

Anchorage Requirements for Deformed Rebars in Grouted Masonry

Current UBC requirements for anchorage of deformed rebars in grouted concrete masonry are based on allowable average bond stresses obtained through tests on concrete. The objectives of this investigation were:

1) to study the bond-slip behavior, under monotonic pullout, of various size rebars embedded in grouted concrete block masonry; and

2) based on these results, to assess the adequacy of current UBC anchorage criteria for such bars.

Tests have been completed on about 80 rebars, varying in size from #4 through #11, with a range of embedment lengths for each bar size. The experimental setup was designed to eliminate the lead-end compressive stress concentrations often observed in ordinary concentric pullout tests. Preliminary results indicate that current UBC criteria provide a significantly lower factor of safety for larger bars (#11) than for smaller ones (#4 and #8). Analysis of failure modes suggests that the anchorage behavior of the larger bars is significantly influenced by the non-homogenous nature of concrete masonry, and may not be predictable on the basis of previous experimental results involving ordinary concrete. Analytical models are being developed to reproduce the essential features of observed anchorage behavior.

Shear Resistance of Short Anchor Bolts under Reversed Cyclic Loading

A critical review is made of previous investigations of the strength of short anchor bolts and studs subjected to monotonic tension and shear. Based on these and additional tests conducted by the author, analytical models are proposed for predicting the strength of anchor bolts subjected to monotonic shear loads, and including the effects of short edge distances. Tests are conducted using various types of supplementary reinforcement to increase the monotonic shear capacity of anchor bolts located close to a free edge.

These results are supplemented by additional tests using reversed cyclic shear loads. Two types of bolts are tested:

1) those located far from a free edge; and

2) those located close to a free edge, but provided with supplementary reinforcement as described above.

Models are proposed for predicting the ultimate resistance of bolts subjected to reversed cyclic shear loads, and recommendations are proposed for the design of such bolts and their supplemental reinforcement.

STRUCTURAL RESPONSE, ANALYTICAL

ANIL K. CHOPRA

University of California, Berkeley

This paper summarizes recently completed and current research at the University of California, Berkeley, sponsored by the National Science Foundation in the areas of Dynamics of Rigid Blocks, Effects of Foundation Tipping on Building Response, Torsionally-Coupled Buildings, Gravity Dams and Arch Dams.

Dynamics of Rigid Blocks

In collaboration with Professor J. Penzien, study of the rocking dynamics of rigid blocks subjected to earthquake ground motion has just been completed [1]. The objectives were to (1) understand the extreme sensitivity of block response to system and ground motion properties, (2) identify probabilistic behavioral trends in spite of the response sensitivity, and (3) evaluate the possibility of estimating the intensity of ground shaking from its effects on tombstones, monumental columns and other similar objects, whether they overturned or remained standing.

A numerical procedure and computer program were developed to solve the nonlinear equations of motion governing the rocking motion of rigid blocks on rigid base subjected to horizontal and vertical ground motion. Systematic trends were not apparent from the response results. The stability of a block subjected to a particular ground motion did not necessarily increase monotonically with increasing size or decreasing slenderness ratio. Overturning of a block by a ground motion of a particular intensity did not imply that the block will necessarily overturn under the action of more intense ground motion. However, the probability of a block exceeding any response level, as well as the probability that a block overturns, increased with increase in ground motion intensity, increase in slenderness ratio of the block, and decrease in its size.

It was concluded that, based on nonlinear dynamic analyses, probabilistic estimates of the intensity of ground shaking may be obtained from its observed effects on tombstones, monumental columns, and other similar objects provided suitable data in sufficient quantity is available. However, these estimates will not be precise because the response of a rocking block is extremely sensitive to variations in systems parameters, contact conditions between the base of the block and the ground, and ground motion details. For the same reasons, deterministic estimates of intensity of ground motion from its observed effects on a single block would be totally unreliable.

Effects of Foundation Tipping on Building Response

The overturning forces developed during vibration of buildings may cause one edge of the foundation to lift-off for short periods of time. The obvious design solution preventing lift-off leads to expensive foundations. Moreover, recent research has shown that foundation tipping can reduce the maximum lateral deformations and forces experienced by the structure in comparison to those it would experience if its base were fixed. Thus, it appears that it may be preferable to permit tipping of the foundation and anticipate such behavior in the design of the structure and its foundation. A study has been initiated in order to (1) develop better understanding of the effects of foundation tipping in earthquake response of buildings, and (2) incorporate these effects in computation of earthquake design forces for buildings.

Torsionally Coupled Buildings

The objectives of a recently completed study [2] of earthquake response of simple one-story torsionally coupled structures in both elastic and inelastic ranges of behavior were to (1) identify the more important parameters that control the response of the system; (2) investigate the influence of the system parameters on the response; (3) evaluate the effects of torsional coupling on lateral and torsional deformations of the system and on deformations of individual columns and walls; and (4) present and evaluate approximate procedures for calculation of yield shear and torque from inelastic response spectra.

The structures considered are symmetrical about one principal axis of resistance, resulting in coupling only between lateral displacement along the perpendicular axis and the torsional displacement. Torsional coupling arising only from eccentricity between centers of mass and elastic resistance is considered.

Systems with several resisting elements, columns and walls were idealized by a single element model. Responses of such a model to a selected earthquake ground motion were computed for a wide range of the system parameters. The response results included maximum lateral and torsional deformations of the system as well as maximum deformations of individual columns. The results demonstrated that the inelastic response is affected by torsional coupling to generally a lesser degree than elastic response. Procedures for estimating, to a useful degree of approximation, the maximum responses of elastic and inelastic systems from the corresponding response spectra, and the maximum deformations of individual columns from the displacements of the center of mass were developed.

Gravity Dams

The objectives of a study nearing completion [3] are to (1) develop effective techniques for including the effects of hydrodynamic and foundation interaction in response analysis of concrete gravity dams to earthquake ground motion, and (2) evaluate the significance of these interaction effects in earthquake response of dams.

An effective analysis procedure, based on the substructure concept and use of generalized coordinates, has been implemented in a computer program for two-dimensional idealizations of dams. The system is considered as composed of three substructures--dam, fluid domain, and foundation rock region--coupled through appropriate continuity conditions and interaction forces at interfaces between substructures. The dam is idealized as a finite element system, whereas the fluid domain is treated as a continuum of constant depth extending to infinity, and the foundation as a visco-elastic halfplane continuum.

The response of idealized dam cross-sections to harmonic, horizontal or vertical ground motion was computed for a range of the important system parameters characterizing properties of the dam, foundation rock, and impounded water. The response of Pine Flat Dam to the S69E component of Taft ground motion only and to the S69E and vertical components acting simultaneously have been computed. These results provide insight into the effects of dam-water and dam-foundation interactions, considered separately or together, in the earthquake response of dams.

Because of dam-water interaction, frequency-dependent additional load and mass terms arise in the governing equations. In the above-mentioned study, these terms were determined from explicit mathematical solutions of the wave equation. This was possible because of the simple geometry assumed for the fluid domain, bounded by a vertical upstream face of the dam, horizontal reservoir bottom, and extended to infinity in the upstream direction. Numerical methods have been developed to compute the hydrodynamic terms associated with irregular fluid domains. The irregular portion of the fluid domain is idealized as a finite element system with a transmitting boundary at its upstream end to simulate the great extent of the water in the upstream direction. Utilizing these procedures for computing the hydrodynamic terms, the effects of the fluid domain geometry on the dynamic response of concrete gravity dams and the significance of hydrodynamic effects in the earthquake response of embankment dams are being investigated.

Arch Dams

The objectives of a study in progress are to (1) develop reliable and effective techniques for earthquake analysis of arch dams including hydrodynamic interaction effects, and (2) achieve better understanding of the hydrodynamic effects and their significance in the response of arch dams to earthquake ground motion.

Based on the substructure concept, earthquake analysis procedures and computer programs have been developed for arch dams. The dam is idealized as an assemblage of thick-shell finite elements. Mathematical solutions of the wave equation have been obtained for idealized fluid domains. Finite element methods to model an irregular fluid domain and a transmitting boundary to simulate the infinite extent of the fluid domain in the upstream direction are being developed to obtain numerical results for practical problems.

References

1. C. S. Yim, A. K. Chopra, and J. Penzien, Report No. UCB/EERC 80/02.
2. C. L. Kan and A. K. Chopra, Report No. UCB/EERC 79/03.
3. A. K. Chopra, P. Chakrabarti and S. Gupta, Report No. UCB/EERC 80/01, in preparation.

ARMEN DER KIUREGHIAN

University of California, Berkeley

This paper summarizes current research at the University of California, Berkeley, sponsored by the National Science Foundation in the areas of Structural Reliability Under Stochastic Loads, Dynamic Response of Light Equipment in Structures, and Seismic Risk Analysis of Lifeline Networks.

Structural Reliability Under Stochastic Loads

The objectives of this study are to (1) develop analytical methods for obtaining the maximum response of structures under combinations of stochastic loads, (2) develop simple approximate methods for use in practice, and (3) critically examine and improve existing methods.

A recently completed study [1] deals with the response of linear, multi-degree-of-freedom structures to stationary excitations, using a modal superposition approach. Analytical solutions are derived for responses to white-noise and filtered white-noise inputs. These solutions include the effect of correlation between modal responses. Hence, they are applicable to structures with closely spaced natural frequencies. For Gaussian excitation, the cumulative distribution and the mean and variance of peak response are obtained. These results account for the dependence between upcrossings of the response process. This study also investigates the range of applicability of the white-noise model as an approximation for wide-band inputs.

Based on the above study, a response spectrum method is developed whereby the cumulative distribution and the mean and variance of the peak structure response to an ensemble of earthquakes are directly obtained in terms of the ordinates of the mean response spectrum and the modal properties of the structure [2]. This method is applicable to structures with any distribution of natural frequencies.

Dynamic Response of Light Equipment in Structures

In collaboration with Professor Jerome L. Sackman, this study concerns the response of light equipment attached in multi-degree-of-freedom structures subjected to earthquake motions. The equipment may be tuned or nearly tuned to a natural frequency of the structure. In the current phase of the study, modal properties of the equipment-structure system are obtained in terms of those of the structure and the equipment alone. These include the interaction between the two subsystems, which can be significant at or near tuning.

Derived modal properties of the equipment-structure system are used in conjunction with a mode-superposition procedure to obtain the response of the equipment to a stationary Gaussian input into the structure. These results form the basis for developing a response spectrum method whereby the cumulative distribution and the mean and variance of the peak equipment response are obtained in terms of the ordinates of the (ground) response spectrum and the modal properties of the equipment and structure subsystems. Particular attention is given to the special case of perfect tuning for which simple approximations are derived. This approach provides an accurate and efficient method which is particularly useful in design situations where a multitude of equipment items or attachment configurations in a given structure are under consideration.

Seismic Risk Analysis of Lifeline Networks

In collaboration with Professors Richard E. Barlow and Karl S. Pister, this study concerns the seismic risk analysis of lifeline networks, such as pipelines and communication and transportation systems. These are modeled as networks of interconnecting links and vertices. Based on new graph theory techniques, a new methodology has been developed for analyzing large-size networks [3]. This methodology can be used to evaluate terminal-pair reliability (i.e., communication between a specific source and a specific terminal), multi-terminal reliability (i.e., a specific source to multiple terminals), or overall reliability (i.e., communication between all terminals) of a given network situated in a seismic region. Measures of importance of selected links and vertices can be determined to recommend improvements relative to seismic risk. The methodology is more general and potentially more efficient than any of the existing methods. A computer code based on this methodology is currently being developed.

References

1. Der Kiureghian, A., "On Response of Structures to Stationary Excitation," Report No. UCB/EERC 79/32, December 1979.

2. Der Kiureghian, A., "Probabilistic Modal Combination for Earthquake Loading," to be presented at the 7th World Conference on Earthquake Engineering, Istanbul, Turkey, September 1980.

3. Barlow, R. E., Der Kiureghian, A. and Satyanarayana, A., "New Methodologies for Analyzing Pipeline and Other Lifeline Networks Relative to Seismic Risk," Report No. UCB/ORC 80-5, March 1980.

S. A. MAHIN AND V. V. BERTERO

University of California, Berkeley

A number of research investigations are currently being conducted at Berkeley under the sponsorship of the National Science Foundation in the area of post-earthquake damage analysis. The overall objectives of these on-going studies are: (1) to identify the structural and/or construction causes of observed earthquake damage and, thereby, assess the adequacy of current seismic-resistant design, analysis and construction methods; (2) to suggest methods for improving current seismic-resistant design practices; and (3) to evaluate and, where necessary, improve methods for strengthening, stiffening, toughening and/or repairing existing buildings to mitigate possible adverse effects of future earthquakes. To accomplish these objectives, detailed field surveys have been made of structural damage following recent earthquakes, and in-depth analyses are being performed on individual damaged buildings. In keeping with the overall objectives of this research, a number of other studies have been initiated to evaluate methods for specifying design earthquakes, to improve mathematical models of structural and nonstructural elements and to formulate design guidelines for certain types of structural systems. Recent research activities are summarized in this paper; more detailed information may be found in the references.

Damages resulting from the 1980 Greenville (Livermore, CA), 1979 Imperial Valley (El Centro, CA), 1978 Miyagi-Ken Oki (Sendai, Japan) and 1977 Caucete (San Juan, Argentina) earthquakes have been surveyed in addition to previous inspections following the 1976 Guatemala (Guatemala City), 1972 Nicaragua (Managua) and 1971 San Fernando, CA, earthquakes. Detailed studies of the performance of building during these earthquakes indicate that each phase in the overall seismic-resistant design, construction and maintenance process must be carefully considered [1,2]. This process should include evaluation of the design earthquake, selection of structural system and materials, proportioning and detailing structural components, prediction of the mechanical behavior of the whole building-soil system, assessment of the reliability of the design, quality assurance inspection and testing during construction, and maintenance during service. Results indicate that great uncertainties still exist in establishing design earthquakes and in analyzing seismic response. In many of the damaged buildings studied inadequate attention was given to the conceptual stages of this process (selection of structural materials, structural systems, nonstructural components and details) as well as to those related to construction and maintenance.

Studies of the Seismic Performance of Buildings

Individual buildings were selected for detailed investigation. Damages in these buildings were documented and information was obtained on their design and construction. Analytical results obtained were reconciled with observed behavior [2]. Detailed results are presented in the references.

Managua Earthquake. Two adjacent high-rise reinforced concrete buildings were studied to determine reasons for the significant differences in their observed performances. One building had a complex structural configuration and an irregular and eccentric lateral force resisting system [3]. It was so extremely damaged that it had to be partially demolished. Analytical results indicated that significant torsion would occur and that masonry infill elements would adversely effect the magnitude and distribution of internal forces. In the other building, large, symmetrically located, coupled walls were used [4]. Although shear failures developed in the coupling girders, size and placement of the walls satisfactorily limited displacements and precluded significant torsional response.

Guatemala Earthquake. Two three-story buildings with R/C moment-resisting frames have been studied to assess, in part, the effect of non-engineered masonry infills on such frames. In one building a constraint method was developed to model the contribution of the infills to the overall frame stiffness [5]. Results indicate that the infills had a significant effect on dynamic characteristics and response. The constraint method permitted identification of the failure mechanism observed in the building. The other building had long span waffle slabs, which were modeled based on the results of a finite element analysis [6]. A nonlinear analysis of this building is being performed to study the progression of response characteristics as elements yield and fail.

Caucete Earthquake. A four-story R/C building using a moment-resisting frame was studied. Frames in the upper three stories were infilled resulting in a "soft-story" type seismic response [7]. Linear elastic and nonlinear dynamic analyses clearly identified the consequences of selecting this combination of structural system and infill elements. A preliminary study has also been performed on steel and R/C tanks which suffered substantial damages during this earthquake.

Imperial Valley Earthquake. A modern six-story R/C building, which suffered significant structural damage, is being investigated [2]. This building utilized moment-resisting frames in one direction but lateral resistance was provided by discontinuous shear walls in the other direction. Thirteen accelerographs recorded the response at various points in this building which will permit thorough evaluation of the response and of analytical methods. A damage survey has been performed and analytical studies are in progress.

Studies Related to Design Earthquakes

Since one of the objectives of the overall investigation is to assess current design methods, a number of analytical studies have been performed to evaluate current methods for specifying seismic design forces and to study various features of ground motions that may necessitate special consideration in design [8]. Studies have previously been reported on the effects of intense, long duration acceleration pulses, representative of recently obtained near-fault ground motion records, and current studies are directed at the effect of ground motion duration and of aftershocks on design requirements [9]. It is not unusual for structures to collapse as the result of cumulative damage from aftershocks following a severe earthquake.

Studies Related to Improvement of Analytical Modelling

Another objective of the overall investigation relates to an assessment of current analytical methods. Previous studies indicated significant limitations of current analytical models based on concentrated plastic hinges, which are often used for nonlinear response analysis [10]. Studies are being performed to better assess the consequences of these limitations especially when significant (gravity) loads are distributed transverse to the axis of members. The contribution of various types of floor systems to the lateral resistance of a structure is being evaluated to improve current modelling capabilities [11]. Other analytical studies are also being conducted to assess the two- and three-dimensional behavior of various types of structural systems and of the ability of current analytical models to predict this behavior. Recommendations for improved modelling and design methods are being formulated on the basis of these results.

References

1. Bertero, V. V., "An Overview of the State-of-the-Art in Earthquake-Resistant Reinforced Concrete Building Construction," Proceedings of the 2nd U.S. Nat'l Conf. on Earthquake Engineering, Aug. 22-24, 1979, Stanford Univ., pp. 838-52.
2. Bertero, V. V., Mahin, S. A., and Axley, J. A., "Lessons from Structural Damages Observed in Recent Earthquakes," Proceedings, 7WCEE, Istanbul, 1980.
3. Lara, O., Bertero, V. V. and Mahin, S. A., "Behavior of the Banco Central Building During the 1972 Managua Earthquake," EERC Report, in preparation.
4. Mahin, S. A. and Bertero, V. V., "Nonlinear Seismic Response of a Coupled Wall System," Jrn. of the Struct. Div., ASCE, Vol. 102, ST9, Sept. 1976.
5. Axley, J. W. and Bertero, V. V., "Infill Panels: Their Influence on Seismic Response of Buildings," Report EERC-79/28, Univ. of Cal., Berkeley, 1979.
6. Sugano, S., "Post Earthquake Damage Analysis of San Juan de Dios Hospital due to 1978 Guatemala Earthquakes," EERC Report in preparation.
7. Lara, O., "Nonlinear Seismic Response of the ENET No. 2 Building During the 1977 San Juan Earthquake," Proceedings, XX Jornadas Sudamericanas de Ingenieria Estructural, Cordoba, Argentina, July 1979.
8. Mahin, S. A. and Bertero, V. V., "An Evaluation of Inelastic Seismic Design Spectra," submitted to Jrn. of the Struct. Div., ASCE.
9. Mahin, S. A., "Effect of Duration and Aftershocks on Inelastic Design Earthquakes," Proceedings, 7WCEE, Istanbul, 1980.
10. Mahin, S. A. and Bertero, V. V., "An Evaluation of Some Methods for Predicting Seismic Behavior of R/C Buildings," Report EERC 75-5, Univ. of Cal., Berkeley.
11. Malik, L. E. and Bertero, V. V., "Contribution of a Floor System to the Dynamic Characteristics of R/C Buildings," Report EERC 76-30, Univ. of Cal., Berkeley.

M. L. WANG
Department of Architecture
University of California, Berkeley

and

S. J. FICCADENTI
Department of Building and Safety
Beverly Hills, California

INTRODUCTION

It is not sufficient that state-of-the-art earthquake engineering knowledge is constantly expanding. For it to be useful, it must be utilized in the design of buildings starting with the architect's earliest concepts. One great concern to many engineers is that on occasion, even fundamental considerations of earthquake engineering in building design are disregarded by the architect. The architectural profession must be alerted to the serious implications of design schemes which are neglectful of good, basic, engineering judgement. Case studies of building failures in earthquakes is a way to highlight the importance of architectural decisions in a building's potential for seismic resistivity. The failure of the Imperial County Services Building in El Centro, Ca., is one such case which emphasizes the extent to which an architectural decision was generally responsible for the fate of a structure in an earthquake.

Although the area most affected by the Oct. 15, 1979, Imperial Valley Earthquake is sparsely populated and not heavily built up, there was a considerable amount of minor damage to homes and shops. The building that was the most severely damaged structurally as a result of the approximately 6.7 magnitude earthquake was the Imperial County Services Building. Ironically, compared to most of the buildings in El Centro, this building is a relatively modern structure which had been designed according to the current Uniform Building Code. In view of the knowledge in earthquake engineering which has existed for decades, the failure of a modern engineered building of only moderately strong magnitude, suggests that the problem is beyond a matter of technical expertise.

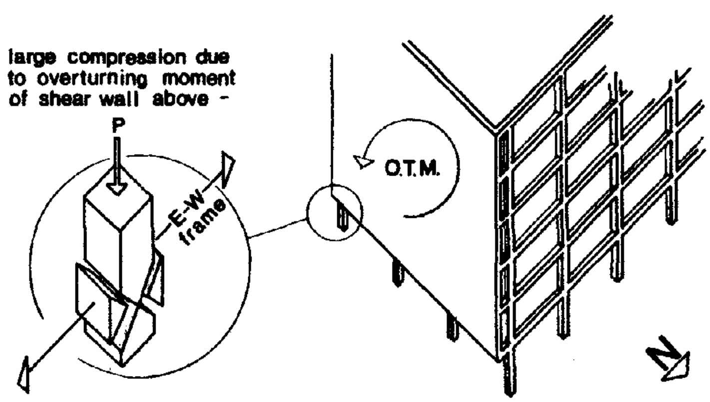
In the following paragraphs, an architectural and structural description of the building will be followed by a brief analysis of the mode of and reasons for failure. Speculation on what the architectural goals of the design for the building were, may reveal the reasoning behind some of the design decisions and bring attention to alternative design concepts that could have avoided the eventual failure without compromising architectural requirements.

DESCRIPTION OF THE BUILDING AND DAMAGE TO THE STRUCTURE

The design for the ICSB (Imperial County Services Building) was completed in 1968 according to the 1967 UBC and was dedicated in 1971. This six story, reinforced concrete building has a regular grid of two foot square columns spaced at twenty-five foot spans. The floor system consists of reinforced concrete slabs and fourteen inch deep, north-south spanning pan joists supported on four longitudinal, reinforced concrete frames.

Although from the exterior, the building is simple looking, a closer examination of its structure reveals that its system of lateral force resistance creates a circuitous, complex path for the forces. Along the east side of the building is a massive shear wall which does not directly continue to the ground. Instead, the east shear wall sits above four concrete columns. One external and three internal ground level shear walls are also oriented in the north-south direction but are only one story high and are assymmetrically arranged in plan. The west shear wall, like the east shear wall, extends from the second level to the top of the building, however, the former is offset only a few feet from one of the ground level shear walls. There are no shear walls in the east-west direction, but rather a frame system of reinforced concrete beams and columns.

There are two essentially different systems of lateral force resistance in this building: a rigid frame system in the east-west direction that is quite flexible, and a shear wall system in the north-south direction that is far more stiff. These two systems actually work against each other in resisting lateral forces. The disparate lateral systems in conjunction with the discontinuous shear wall on the east side of the building was the most responsible for the ultimate collapse of the east line of columns. The failure mechanism was initiated by east-west frame action which resulted in X-cracking in the flexible direction of the building, at the bases of the east line of columns. The north-south component of the shock caused the huge and heavy discontinuous end shear walls to overturn in the transverse direction of the building. On the east side, the columns were unaided by any ground level shear walls in taking the compressive force from the shear wall above. These columns already suffered cracking from frame action, and explosively failed in compression resulting from the overturning of the east end shear wall. In all the columns that failed, the weak points were at the bases. There was only a minimal amount of transverse reinforcement to confine the concrete at the bases, and the steel bars easily buckled in the frame direction. The wedge shaped pieces of concrete attest to the 45 degree cracking initiated by frame action which created a hinge in the longitudinal direction.



FAILURE MECHANISM

CONCLUSION

Shear walls that are discontinuous to the ground (such as columns supporting shear walls or cantilevered shear walls), have been quite popular in modern architecture and often have the purpose of opening up the ground floor. The motivation hehind the decision to use a particular combination of discontinuous shear walls and moment resisting frames in the ICSB, appears to be requirements for fenestration design as well as an open first floor. Preliminary plans should have considered alternative architectural designs such that the structure could be designed to fit the architectural criteria without drastic consequences in a moderate to strong earthquake. There are several immediately obvious alternatives of structural systems, configurations, and materials, which compared to those of the ICSB, would mitigate the tendency for a structural failure in an earthquake:

a. frames in two directions
b. shear walls continuous to the ground in two directions, at least at the core of the plan
c. use of less heavy materials such as lightweight concrete in at least part of the construction
d. use of more ductile materials, such as steel.

It is generally recognized by practitioners that any building code can at most be a guide to the designer. Nonetheless, a building such as the ICSB could have had a better chance of surviving the 6.7 magnitude shock if it were designed according to a later and more refined UBC. Although Codes subsequent to the 1967 UBC also do not have restrictions on discontinuous shear walls or building configuration in general, there are more stringent concrete column confinement requirements. In addition, there is a much higher lateral force coefficient, C, that the 1976 UBC would assign to a building whose period is like that of the six story ICSB. The base shear that the structure would be designed for (F=KCISWZ) would have approximately doubled in value between the 1967 and 1976 Codes.

Unfortunately, the ICSB is not an extremely rare example of a building whose structure invites disaster in an earthquake despite being up to Code. Although the Code is constantly being improved, there is a limit to how much restriction in design it can or should impose on the profession. It is fortunate that architects still possess a relatively great amount of freedom in architectural decisions even in the highest earthquake zones. At the same time, architects should have a thorough understanding of how forces act upon structures. They must ultimately rely upon their own and their engineer's good judgement in designing a building to resist seismic forces. It is critically important that intensified attention is directed toward the impact of architectural decisions on the structural behavior of buildings in earthquakes.

GEORGE W. HOUSNER and MEDHAT A. HAROUN

California Institute of Technology

Theoretical and experimental investigations of the dynamic behavior of ground-supported, deformable, cylindrical liquid storage tanks were conducted. The study was carried out in three phases: A) a detailed theoretical treatment of the coupled liquid-shell system for tanks rigidly anchored to their foundations, B) an experimental investigation of the dynamic characteristics of full-scale tanks, and C) a development of an improved design procedure.

A) Theoretical Analysis

(i) Free Lateral Vibrational Modes

The natural frequencies of vibration and the associated mode shapes were determined by means of a discretization scheme in which the elastic shell is modeled by finite elements and the liquid region is treated as a continuum by boundary solution techniques. In this approach, the number of unknowns is substantially less than in those analyses where both tank wall and liquid are subdivided into finite elements.

The analysis was applied to compute the $\cos\theta$-type modes for which there is a single cosine wave of deflection in the circumferential direction; these modes are strongly excited by rigid base motion. A significant difference was found between the dynamic characteristics of "broad" and "tall" tanks, and between the hydrodynamic pressure distributions induced in these tanks. The analysis was also extended to investigate the coupling between liquid sloshing modes and shell vibrational modes; it was found that the coupling is weak, and consequently, the convective pressure can be evaluated with reasonable accuracy by considering the tank wall to be rigid. A parametric study was also carried out to investigate the effect of the initial hoop stress due to the hydrostatic pressure, the effect of soil deformability and the effect of roof rigidity upon the vibrational characteristics.

(ii) Earthquake Response Analysis

The effective external load vector for the tank wall was found by employing the expression of the work done by external loads (inertia forces and hydrodynamic pressures) through arbitrary virtual displacements.

For a perfectly circular tank, the external loads are functions of $\cos\theta$ only; and consequently, the earthquake response can be obtained by superposition of the vertical modes corresponding to $n = 1$ only. It was found that the flexibility of the tank walls has a significant effect on the seismic response of both broad and tall tanks. The dynamic stresses are much greater than those computed assuming rigid walls. These results were further substantiated by comparing the computed response of aluminum tank models with that measured by shaking table tests conducted at U.C. Berkeley. This comparison also indicated that the computed fundamental frequency is higher than the measured frequency. An analysis was also made to investigate the effect of non-circular irregularity of the cross sections of flexible tanks; however, the fact remains that the magnitude and distribution of fabrication error cannot be predicted. It is important to note that a recent study at Caltech showed that buckling of tank models depends largely on the stresses associated with the cosθ-type modes.

B) Vibration Tests of Full-Scale Tanks

A series of ambient and forced vibration tests of three full-scale tanks was conducted to determine the natural frequencies and, if possible, the mode shapes of vibration and to select two tanks on which permanent instruments would be installed to record future earthquakes. Measurements of the ambient and forced vibrations were made at selected points along the shell height, at the roof circumference, and around the tank bottom. The first series of tests were conducted to measure the axial pattern of shell vibrational modes. The objective of the second series of tests was to monitor the motion around the circumference. A vibration generator was used in the sinusoidal steady-state resonant tests; it was anchored to a concrete slab resting on the ground adjacent to the tank. The horizontal sinusoidal force exerted by the shaker was transmitted through the ground and produced small amplitude vibrations of the tank. One phenomenon that was clearly observed in the recorded motion was that cosnθ-type vibrations of the tank wall were developed. The foundation conditions had an influence on the response of the cosθ-type modes. Comparison with previously computed mode shapes and frequencies showed good agreement with the experimental results.

C) Seismic Design

The principal aim of the final phase of research was to devise a practical approach which would allow, from the engineering point of view, a simple and satisfactorily accurate estimate of the dynamic response of tanks to earthquakes. A mechanical model which takes into account the deformability of the tank wall was developed and its parameters were displayed in charts. These curves facilitate the calculations of effective masses, their centers of gravity and the periods of vibration. The effective masses m_r, m_f, and m_s correspond to the forces associated with ground motion, wall deformation relative to the ground, and liquid sloshing, respectively. Once the parameters of the mechanical model of the particular tank under consideration are found, the maximum seismic loading can be predicted by means of a response spectrum characterizing the design earthquake.

Further Research

The foregoing analysis is applicable only to tanks that are anchored to a rigid base. The support of an unanchored tank can resist downward forces while the uplift of the tank is prevented only by the dead weight of the tank and its content. As soon as any vertical tensile stress, induced by earthquake motion, exceeds the stress due to the dead load, uplift will occur; and consequently, one cannot assume the tank to be cantilevered from its base. An approximate analysis is being developed in which a part of the tank lifts off the foundation while the remainder of the tank, wherever the contact forces are downward, is still supported by the base. Such analysis will be employed to understand and interpret the damage of unanchored liquid storage tanks at El Centro during the earthquake on October 15, 1979.

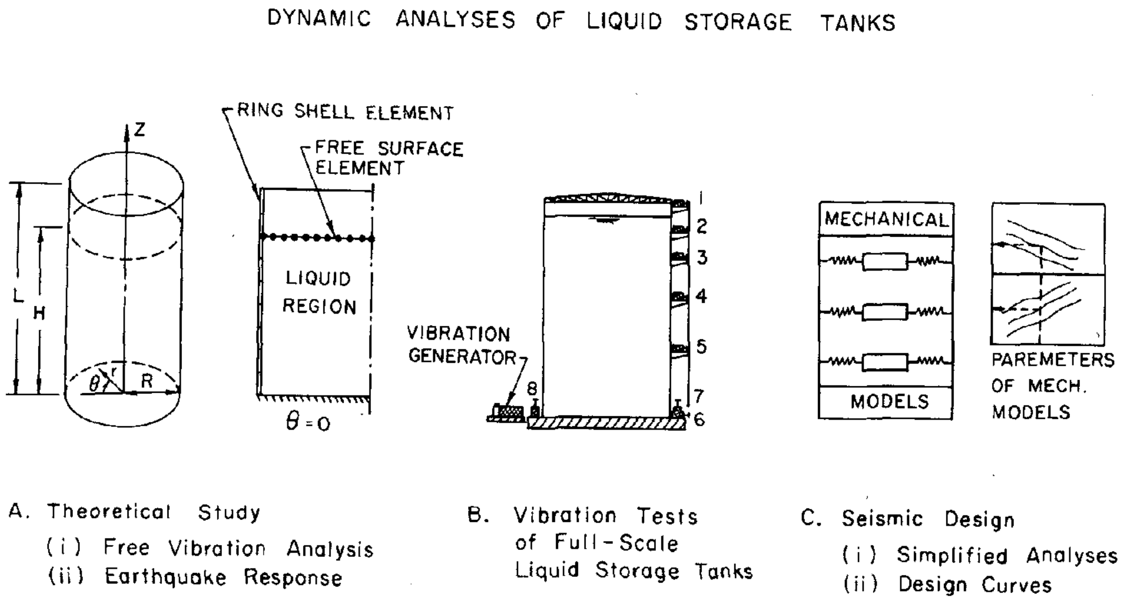


Figure 1

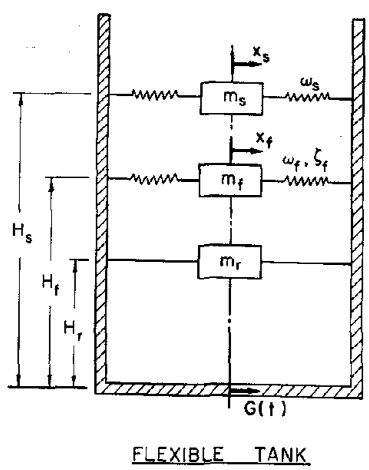


Figure 2

W. D. IWAN

California Institute of Technology

Research sponsored by the National Science Foundation is being conducted in the general area of the earthquake response of nonlinear structural, soil-structure and equipment systems. This research has been organized into a number of specific projects as indicated below.

Response of Yielding Systems

The objective of this project is to better understand and be able to predict the earthquake response of yielding systems. The approach which has been adopted involves: 1) detailed simulation studies of the random response of the bilinear hysteretic system, 2) separation of the response process into an "oscillatory" and "drift" component, 3) development of an approximate analytical-empirical model for each response component, and 4) recombination of the response processes to obtain the overall response statistics.

This program has yielded an analytical-empirical model which accurately predicts the transient response of the bilinear hysteretic system. It has also provided a new model for deducing inelastic response spectra. Some of the research results are reported in references [1] and [2].

Inelastic Response Spectra

The objective of this research project is to explore the possibility of deducing inelastic response spectra from elastic spectra. The approach which has been used in this investigation is based on numerical simulation studies of six different inelastic systems at nine nominal natural periods using an ensemble of twelve earthquake time histories. Spectral errors associated with various existing and proposed inelastic spectrum generating techniques have been examined.

A new empirical inelastic spectrum generating technique has resulted from this project. In addition, the project has provided a more complete understanding of the nature of the spectral errors associated with inelastic spectral modeling. The major results of this research are discussed in reference [3].

Transient Random Response of Nonlinear Discrete Systems

The objectives of this research project are: 1) to develop analytical techniques for determining the transient response statistics of randomly excited nonlinear systems including peak response statistics and 2) to determine the relationship between the peak response of linear and nonlinear systems subjected to the same excitation. The approach which has been employed is an extension of the method of equivalent linearization. This results in a deterministic ordinary nonlinear differential equation for the response covariance matrix which may be either solved numerically or treated by approximate analytical techniques. The limiting decay rate of the first crossing density is estimated by approximating the clump conditional probability density. This leads to a statistical estimate of the peak response of the system.

The results of the project to date include: 1) a consistent analytical technique for obtaining response statistics for nonlinear systems, 2) a simplified technique for determining the first passage probability density, 3) a simplified technique for generating earthquake time histories corresponding to prescribed response spectra and 4) an analytical technique for deducing nonlinear response spectra from linear response spectra. Some of the results of this research are presented in references [4] and [5].

Response of Continuous Systems

The objective of this project is to develop simplified analytical-numerical methods for determining the response of nonlinear continuous systems. The approach which is being investigated is to generate a finite element model of the system and then perform an analytical element linearization. Since the linearized element properties will in general depend upon the solution, an iterative procedure is required.

Three different linearization schemes have been considered; equation difference minimization, strain-energy difference minimization and "stress" difference minimization. The approach is being applied initially to problems of the steady-state harmonic and stationary random response of simple beam and plate systems. The results of this research will be published in the near future.

Strain-Space Plascitity Theory

The objective of this research is to develop a consistent and computationally efficient strain-space analog to the classical plasticity theory. It is believed that such a tool will open the door to more accurate and efficient solution of problems involving plastic behavior. This includes both structural, soil, and soil-structure applications.

A new compatible strain-space theory has been developed and a number of inelastic soil-structure interaction problems have been examined using this theory. The effects of domain size, mesh size, and yield model have been studied. The results of this investigation will be published in the near future.

References

1. R. L. Grossmayer and W. D. Iwan, "Some Observations on the Effective Period and Damping of Randomly Excited Yielding Systems," Proceedings, 2nd U.S. National Conference on Earthquake Engineering, Stanford, 1979.

2. R. L. Grossmayer and W. D. Iwan, "A Linearization Scheme for Hysteretic Systems Subjected to Random Excitation," accepted for publication in the International Journal of Earthquake Engineering and Structural Dynamics.

3. W. D. Iwan, "Estimating Inelastic Response Spectra from Elastic Spectra," accepted for publication in the International Journal of Earthquake Engineering and Structural Dynamics.

4. W. D. Iwan and A. B. Mason, "Equivalent Linearization for Systems Subjected to Nonstationary Random Excitation," accepted for publication in the International Journal of Non-Linear Mechanics.

5. A. B. Mason and W. D. Iwan, "A New Approach to the First Passage Problem in Random Vibration," Proceedings, 15th International Congress of Theoretical and Applied Mechanics, Toronto, 1980.

PAUL C. JENNINGS

California Institute of Technology

Earthquake engineering research sponsored by the National Science Foundation is being performed in the areas of analytical studies of structural response, including problems in system identification and structural dynamics, and in the characterization of strong ground motion.

Analytical Studies of Earthquake Response

Two recent Ph.D. theses on the development and application of techniques of systems identification to the earthquake response of structures have permitted the determination of the dynamic properties of buildings from their earthquake response (Beck, 1978; McVerry, 1979). In addition to the theses, which are available as Caltech EERL reports, the results are summarized in two papers soon to appear in the International Journal of Earthquake Engineering and Structural Dynamics. The two approaches are complementary; one works in the time domain whereas the other performs analyses in the frequency domain. Although they are theoretically equivalent, the details of a specific application may make one method preferable over the other in practice. In application to earthquake response data, primarily from the San Fernando earthquake, it has been possible to determine natural periods, modal dampings and modal participation factors in numbers and to a degree of accuracy not achieved by other methods. The properties can be determined over the entire duration of earthquake response or equivalent linear properties of the structure for shorter segments of time can be found. For highly nonlinear response, such as shown by the Orion Avenue Holiday Inn in the San Fernando earthquake, or more recently by the Imperial County Services Building in the October 15 earthquake, the methods, which are based on linear models, do not work well, and we are currently thinking about the more difficult problem of systems identification of nonlinear structures.

The problem of structures shaken so hard that they begin to tip, in the sense of losing partial contact with their foundations, is being examined in two studies. In one study (Rutenberg, et al., 1980) of the successful performance of Veterans' Hospital Building 41 during the San Fernando earthquake, only about two-thirds of the high resistive capacity of the structures could reasonably be attributed to the basic strength of the materials and structural elements according to usual methods of analysis. The most likely reason for the remaining capacity demonstrated by the building appears to be nonlinear soil-structure interaction, including nonlinear soil behavior and partial uplift of the foundation. In another study comprising the doctoral thesis of John Psycharis, the basic mechanics of rocking and incipient tipping are being analyzed. The structures considered include rigid blocks, simple one-degree-of-freedom and multi-degree-of-freedom oscillators and a continuous shear beam. They are based on a variety of foundation models including a rigid half-space, a Winkler foundation and equivalent two spring models. The results contain fairly extensive analyses of the problem of rocking and tipping for the simpler systems, including approximate models that may prove useful in design. For the more complex systems, the results consist of derivations of the equations of motion, some applications of Laplace transform theory and example calculations of response to strong earthquakes. A report is expected to be available later this year.

A third study concerns the problem of so-called "silent" boundaries. This problem occurs in finite element calculations for large systems wherein special boundary elements are introduced at the edges of the mesh selected for the problem. The purpose of these elements is to simulate the more costly alternative of extending the mesh to a distance sufficient to prevent unwanted reflections from the boundary of the mesh. Some progress on this difficult problem has been made by Martin Cohen, who has adapted and developed the idea of a paraxial boundary to finite element calculations and has made comparisons of its behavior with the commonly used viscous boundary elements. The comparison includes theoretical analyses of wave reflection coefficients and numerical comparisons via prototype problems in the dynamics of soil-structure interaction. We expect these studies to be completed this summer.

Characterization of Strong Ground Motion

Studies in this area are related to the recent completion of methods for determining the local magnitude, M_L, of earthquakes from strong motion instruments, both accelerographs and seismoscopes (Kanamori and Jennings, 1978; Jennings and Kanamori, 1979). Perhaps the most interesting result from the second study was the estimation of the local magnitude of the San Francisco earthquake of 1906 ($M_s = 8\frac{1}{4}$). Using records from several seismoscope-like instruments, it was concluded that the local magnitude of the earthquake lay in the range from 6-3/4 to 7. Continuing studies in this area are an analysis of the local magnitude of the Imperial Valley earthquake of August 15, 1979 and a statistical study of response spectra of different earthquakes of the same local magnitude, recorded at the same distance.

References

Beck, James L., "Determining Models of Structures from Earthquake Records," Ph.D. Thesis, Calif. Inst. of Tech., EERL Report 78-01, July 1978.

Kanamori, H. and P. C. Jennings, "Determination of Local Magnitude, M_L, from Strong-Motion Accelerograms," Bull. Seism. Soc. Amer., vol. 68, no. 2, pp. 471-485, April 1978.

Jennings, P. C. and H. Kanamori, "Determination of Local Magnitude, M_L, from Seismoscope Records," Bull. Seism. Soc. Amer., vol. 69, no. 4, pp. 1267-1288, August 1979.

Lee, D. M., Jennings, P. C. and G. W. Housner, "A Selection of Important Strong Motion Earthquake Records," Calif. Inst. of Tech., EERL Report 80-01, January 1980.

McVerry, Graeme E., "Frequency Domain Identification of Structural Models from Earthquake Records," Ph.D. Thesis, Calif. Inst. of Tech., EERL Report 79-02, October 1979.

Rutenberg, A. V., Jennings, P. C. and G. W. Housner, "The Response of Veterans Hospital Building 41 in the San Fernando Earthquake," Calif. Inst. of Tech., EERL Report 80-03, May 1980.

DARIO A. GASPARINI AND AMITABHA DEBCHAUDHURY

Case Western Reserve University

Our research in earthquake engineering is focused on two major areas; random vibration analytical techniques and passive systems for vibration control. The research has been partially funded by NSF Grant Number ENG-77-19364 and conducted in collaboration with Mr. Lawrence W. Curry. What follow are summaries of our progress in these two areas and brief descriptions of our ongoing efforts.

Random Vibration

Utilizing the state formulation, we have obtained analytical results for the evolution of the covariance matrix between two modal state vectors for systems excited by non-white (or white) non-stationary excitation having a linear strength function. We are able, therefore, to compute analytically time histories of variance or RMS responses of any linear MDOF system which has been decoupled into modes and subjected to excitation having a piece-wise linear strength function. Using the time histories of RMS responses and Rice's results, we can compute, very simply, evolutionary probabilities of exceeding very high thresholds.

A computer program to perform such random vibration analyses has been written and is available. In collaboration with Professor George Gazetas, the formulation has been used to study the behavior of shear beam systems.

We are presently attempting to obtain statistics of evolutionary RMS responses of stochastic linear systems, i.e., systems whose dynamic properties (frequency, damping, etc.) are random. The feasibility of implementing vector-valued excitation and piece-wise linear random vibration analyses of non-linear systems is also being studied. Additionally, we are incorporating into the program existing (approximate) first passage results for lower thresholds so that exceedance probabilities for a range of responses are available to designers.

Passive Systems for Vibration Control

Viscoelastic materials are widely used to reduce vibration in mechanical systems and products. A major objective of our research is to determine if it is feasible to use such materials for controlling the vibration of civil engineering structures.

To determine the effect of viscoelastic materials on the damping of a structure, a finite element program for computing steady state responses of composite viscoelastic systems to harmonic excitation has been developed. We are able, then, to compute the dynamic amplification functions of composite systems from which we infer effective damping. We have used the program to analyze two proposed composite systems. One is a steel braced frame with a vertical viscoelastic layer and the other is a steel rigid frame with (viscoelastic) infill panels. In both cases, the viscoelastic materials significantly increased the damping of the frames. We have also determined that predicting damping by weighting each material's contribution by its strain energy may be an unconservative procedure.

We are presently formulating design criteria for damping materials and, concurrently, attempting to identify suitable materials. To achieve these objectives, we are investigating the non-linear behavior of the proposed composite systems under extreme earthquake loads.

In addition, two allied although distinct efforts are planned. One will investigate the feasibility of using energy dissipating materials between closely spaced buildings. Another will examine the use of frictional mechanisms which are intended to function solely during extreme earthquakes.

References

1) Gasparini, D.A., "Response of MDOF Systems to Non-Stationary Random Excitation", Journal of the Engineering Mechanics Division, ASCE, Vol. 105 No. EM 1, February 1979.

2) Gasparini, D.A., DebChaudhury, A. and Curry, L.W. "Damping of Frames with Constrained Viscoelastic Layers", Journal of the Structural Division, ASCE, Vol. 106, No. ST 1, January 1980.

3) Gasparini, D.A. and DebChaudhury, A. "Response of MDOF Systems to Filtered, Non-Stationary Random Excitation", Proceedings of the Third ASCE Engineering Mechanics Division Specialty Conference, U. of Texas at Austin, September 1979.

4) Gasparini, D.A.;Curry, L.W. and DebChaudhury, A. "Behavior of Frames with Viscoelastic Infill Panels". Submitted to the ASCE Structural Division Journal.

ARTHUR A. HUCKELBRIDGE

ROBERT M. FERENCZ

Case Western Reserve University

SEISMIC OVERTURNING EFFECTS

Historically, overturning resistance in structural systems has been provided primarily by the dead weight of the structure acting through a lever arm equal to some fraction of the base dimension. A growing awareness among code groups and designers of the lateral load magnitudes associated with extreme seismic events has caused an increased interest in overturning effects and design strategies which might effectively accommodate them.

Design strategies for overturning effects can be broadly broken into two groups; those which would provide a capacity equal to or greater than that produced by predicted extreme lateral loading and those which would limit capacity to only that provided by the dead weight and the appropriate base dimension. The latter strategy obviously implies a potential for transient uplift of portions of the foundation and a resulting complex, nonlinear response. This strategy, nevertheless, has very attractive attributes, both structural and economic, and is therefore being investigated by the authors.

RESEARCH EFFORT UNDERWAY

The investigation undertaken can be separated into three areas; i) characterization of overturning behavior of various structural systems, ii) development of efficient, practical analytical tools and, iii) development of effective preliminary design tools.

Characterization of Overturning Behavior

In the first area of investigation a variety of structural types are being subjected analytically to a number of extreme seismic excitations and the resulting behavior characterized. For this purpose full nonlinear analyses are being utilized, a proven technique for predicting such response.[1,2]. Structural types being investigated include medium to high rise moment frames, braced frames, shear walls, core walls and coupled shear walls. The excitations being utilized are actual recorded accelerograms, amplified where necessary to represent extreme seismic events.

Development of Analytical Tools

In the second area of investigation a practically oriented nonlinear seismic analysis program, DRAIN-2D [3] is being modified to incorporate limited substructuring capability, in order to more efficiently treat localized nonlinearity such as foundation uplift. Through this technique a linearly behaving superstructure can be represented by the first few normal modes of vibration, thus drastically reducing the number of degrees of freedom and computational effort involved in the analysis.

Development of Design Tools

Particularly in the preliminary design stage of a structural system, simplified means of estimating often complex responses are required. For that reason an effort is planned with the objective of developing such tools directed toward the nonlinear overturning problem.

An obvious model is the Newmark Design Response Spectrum approach[4], widely recognized and used. This technique was developed for bilinear elasto-plastic systems, however, and cannot be a priori assumed applicable to a bilinear elastic system, such as is characteristic of a simple uplifting frame. An attempt to extend this technique to such bilinear elastic systems is currently in progress.

RESULTS TO DATE

For all structures characterized thus far, allowing transient uplift has expectedly produced a reduction in lateral load levels when compared to a corresponding fixed base response. Depending on excitation level, structural type, etc. reductions can quite easily be on the order of 50%. Depending upon the extent of hysteretic behavior in the superstructure, however, there may be some degree of loss of drift control with foundation uplift. The superstructure of a simple braced frame or moment frame, for example, may well remain linear and subsequently suffer a substantial loss of drift control. A dual system such as a moment frame/shear wall or coupled shear wall, on the other hand, may exhibit considerable hysteretic behavior in the coupling elements and thus retain essentially all of the drift control of the fixed base counterpart.[5] It should be mentioned that much of the increased drift of the fully linear superstructures is, however, due to rigid body rotation and not necessarily indicative of high damage levels.

The remaining areas of investigation mentioned previously are not yet at a stage for reporting of results. Work is continuing and positive results are soon anticipated. An eigen problem capability, using the subspace iteration technique, is in place in the program and operational. Decisions are still being made, however, concerning procedures for effective matrix partitioning.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. PFR-7808013. This support is gratefully acknowledged by the authors.

REFERENCES

1. Clough, R.W. and Huckelbridge, A.A., "Preliminary Experimental Study of the Seismic Uplift of a Steel Frame", U.C. Berkeley Report EERC 77/22, 1977

2. Huckelbridge, A.A., "Earthquake Simulation Tests of a 9-Story Steel Frame with Columns Allowed to Uplift", U.C. Berkeley Report EERC 77/23, 1977

3. Kanaan, A and Powell, G.H., "General Purpose Computer Program for Inelastic Response of Plane Structures", U.C. Berkeley Report EERC 73/5, 1973

4. Newmark, N.,Blume,J. and Kapur,K., "Seismic Design Spectra for Nuclear Power Plants", Journal of the Power Division, ASCE Vol. 99, N. PO2, Nov. 1973

5. Huckelbridge, A.A. & Ferencz, R.M., "Overturning Effects in Stiffened Building Frames", submitted for publication.

CHRISTIAN MEYER
MASANOBU SHINOZUKA

Department of Civil Engineering and Engineering Mechanics
Columbia University

This paper summarizes research currently in progress at Columbia University to develop a general methodology of predicting the earthquake reliability of damaged reinforced concrete buildings. This research is sponsored by the National Science Foundation and has been in progress not for very long. This summary will therefore concentrate mostly on research objectives and methodologies rather than results. The project is subdivided into four phases which are briefly outlined below.

Damage Assessment Model

The development of a model for defining structural damage requires the consideration of a number of factors: a) the model should be as free from subjective judgment as possible; b) it should be relatively easy to compute the damage index on the basis of field observations; c) the model should adequately represent the amount of stiffness degradation; d) it should reflect the probabilistic nature of damage as analytically as possible to make the reliability analysis tractable.

Developing such a damage model to predict the residual strength or stiffness of a reinforced concrete member is fundamental to the project. We are currently attempting to correlate the degree of stiffness degradation with the visible amount of cracking, taking into account the severity of cracking, spalled-off or loose and pulverized concrete, bond failures, etc. For this purpose we are relying heavily on a number of well-documented test results to calibrate the free parameters in our damage or stiffness degradation parameter.

Mathematical Model for Reinforced Concrete Behavior

Modeling studies of reinforced concrete behavior have progressed in recent years to account for stiffness degradation due to cracking, bond-slip of the reinforcement, as well as stress transfer between concrete and steel bars, aggregate interlock and dowel action. We intend to employ the finite element method to further the understanding of concrete members under severe cyclic loading. The results of these studies will be used to develop a simple though accurate model suitable for nonlinear dynamic analyses of reinforced concrete buildings.

Dynamic Response Analysis of Reinforced Concrete Buildings

Once an accurate though moderately simple mathematical model is available it will be relatively straightforward to implement it into a computer program that permits the analysis of the dynamic response of structures to strong ground motions. Because the nonlinear nature of the response eliminates most existing general-purpose analysis programs from consideration, we will probably choose to adopt the NONSAP program to our purposes.

The major modification consists of incorporating into the program the mathematical model describing the stiffness degradation of concrete under cyclic loading. The degree of stiffness degradation is defined by a set of stiffness degradation parameters, which are zero for an undamaged structure. Subsequent excursions of the member into the nonlinear range will introduce damage as measured by the parameters. A damaged building is then characterized by a set of parameters with nonzero values prior to any response analysis. Since, in general, the past load history is not known exactly for a damaged building, the substitution of the damage or stiffness degradation parameter proves to be very useful.

Seismic Reliability of Damaged Buildings

The practical value of a single deterministic response analysis is limited, no matter how refined the mathematical model, because of the uncertainties associated with future seismic events. In order to arrive at useful and practical statements regarding the safety of buildings, recourse to statistical methodologies has to be taken. Recognizing that intensity and time of occurrence of seismic events are probabilistic, we are attempting to simulate past load histories on the basis of known or assumed damage states in order to estimate the extent of statistical variation in the stiffness degradation, using numerical simulation techniques such as the Monte Carlo method.

Based on the analysis and simulation we will construct initial damage probability matrices which define the damage state or stiffness degradation parameters as functions of the modified Mercalli intensity, of undamaged structures. The next step requires the establishment of conditional damage probability matrices which indicate the damage probability as a function of both earthquake intensity and prior damage. Thus it will be possible to characterize the process in which the structural damage will grow with time in the seismic environment considered. Such information will provide vital assistance in estimating the reliability of a damaged structure for continued use and will be indispensable in devising repair and strengthening strategies.

Summary

The question of residual strength of damaged buildings is without doubt an important one and will be of increasing concern to public officials charged with disaster mitigation following major earthquakes. The research described is intended to develop a methodology for rapid safety evaluation of buildings after catastropic earthquakes.

W. McGUIRE, J. F. ABEL, D. P. GREENBERG

Cornell University

The principal objective of the research described below is the development of interactive computer graphics capability for the static and dynamic nonlinear analysis and design of three-dimensional steel frame structures. It is being supported by the National Science Foundation under Grant No. PFR-78-15357.

The research is being conducted by the Department of Structural Engineering in Cornell's Laboratory of Computer Graphics. The laboratory is designed to provide convenient interactive use of graphics equipment that is supported by a powerful 32-bit, virtual-memory minicomputer and that is capable of producing color displays and complex dynamic black and white vector displays. The graphics equipment of primary interest consists of vector refresh displays hardwired for all three-dimensional and perspective transformations, frame buffers for color raster displays, a video disk for rapid buildup and playback of dynamic color raster images, and digitizing tablets that supplant the traditional terminal keyboard for most of data input and program control. The research is directed towards finding ways in which the attributes of such a system can be used most effectively to facilitate the practical application of advanced methods of analysis and design of steel structures. An integrated analysis/design system is planned. Current research can be placed in five categories: 1) preprocessing, 2) static analysis and design, 3) dynamic analysis, 4) postprocessing, and 5) data base management.

Preprocessing

A preprocessor for the graphical description and input of three dimensional frame problems has been developed. Its capabilities include frame geometry generation, frame assembly, member selection, boundary and constraint condition prescription, loading definition, and general editing. Components of the preprocessor are entered by pointing to a list on a master control menu using a cursor controlled by the movement of the pen on the digitizing tablet. Both regular and irregular frame configurations can be rapidly created through use of the digitizing tablet as a graphic means for communicating geometric and topologic information from the user to the machine. Trial cross-sectional shapes may be selected by pointing to a displayed list of member sizes. Nonstandard shapes may also be prescribed. Useful properties, such as element yield surfaces, may be displayed. There are provisions for nodal point and distributed static loads, and specifications of ground motion characteristics and response spectra. User convenience is emphasized not only through the ease of inputting problem-description data but also through flexibility in the order in which the components of the preprocessor may be accessed.

Static Analysis and Design

An objective is to develop a static analysis/design system that will give a realistic picture of the manner in which a structure responds to both service and ultimate limit-state loads. The start that has been made in this direction for planar frames is described in Reference 1. Capability similar to this is being extended into three dimensions as part of the current research. For frame structures a discrete element capable of modelling realistically the combination of axial force, biaxial bending, and torsion that occurs in many building frame members is needed. This implies the ability to include such effects as initial imperfections, residual stresses and spreading plastification. The thrust of much of the effort in the static analysis/design portion of the research is towards the development and incorporation of such an element. Both faceted and continuous yield surfaces are being evaluated for their effectiveness in representing and controlling cross section yielding.

Dynamic Analysis

Initial effort in dynamic analysis has been directed toward the linear analysis of two- and three-dimensional frames under various forms of base excitation. Present capability includes explicit and implicit methods for the direct integration of the equations of motion and provision for mode superposition. Response spectrum analysis techniques are being incorporated. This portion of the research has involved the development of a library of fundamental operations designed for efficiency of application in the virtual memory minicomputer environment. Transient analysis capabilities will be extended to nonlinear problems in the near future.

Postprocessing

Postprocessing includes all features that aid the understanding and interpretation of the results of an analysis or trial design. Provisions are made for conventional printed or plotted output, but the research stresses the development of black-and-white and color graphics displays that can simplify the task of the analyst/designer and reduce the possibilities for error or misinterpretation. Some of these displays are extensions or modifications of the two-dimensional, nonlinear static analysis postprocessing capability reported in Reference 1. Others include more or less conventional black-and-white time-history displays and dynamic displays of deflecting frameworks. Considerable effort is being applied to the exploration of ways in which color can be used effectively to picture and explain three-dimensional effects.

Data Base Management

Research of the type described involves data base problems of considerable magnitude. The gross organization of the data base takes into account the fact that there are at least three distinct types of information that will be manipulated and produced: 1) permanent data (member section properties, standardized loads, etc.), 2) problem description geometry (geometry, topology, etc.), and 3) structural response data (member forces, time varying displacements, etc.). A question that must be resolved is whether, for a system such as this, the data base should be a passive one (managed entirely from within the applications software) or an active data base with separate data-base management software. The present effort tends toward the former approach in that an application-oriented master control program is being designed and implemented to combine the control of the various preprocessing, analysis, postprocessing, and design aspects with the appropriate management of data flow, storage, and retrieval.

REFERENCE

1. Gross, J. L., Mytryn, T. A., McGuire, W., "Computer Graphics and Nonlinear Frame Analysis," Proceedings, 7th Conference on Electronic Computation, St. Louis, ASCE, 1979.

P. V. THANGAM BABU
Newfoundland Oceans Research and Development Corporation
St. John's, Nfld., Canada

D.V. REDDY
Ocean Engineering
Florida Atlantic University
Boca Raton, Florida

M. AROCKIASAMY
Faculty of Engineering and Applied Science
Memorial University of Newfoundland, St.John's, Nfld., Canada

1. INTRODUCTION: Finite Element and Lumped Parameter models are formulated for the seismic response of floating platforms taking into account the fluid compressibility and the platform flexibility. The study is an extension of earlier work in which the structure-fluid coupling was considered with different degrees of simplification - incompressible fluid with a flexible body, and compressible fluid with a rigid body (Refs. 1, 2, and 3).

2. MODELING

2.1 Finite Element Analysis: Using an Eulerian pressure formulation, the coupled equations of motion are obtained as follows:

$$\begin{bmatrix} \overline{M} & 0 \\ \rho\overline{L}^T & 0 \end{bmatrix} \begin{Bmatrix} \ddot{\overline{\delta}} \\ \ddot{\overline{\phi}} \end{Bmatrix} + \begin{bmatrix} \overline{C} & 0 \\ 0 & \overline{D} \end{bmatrix} \begin{Bmatrix} \dot{\overline{\delta}} \\ \dot{\overline{\phi}} \end{Bmatrix} + \begin{bmatrix} \overline{K} & \overline{L} \\ 0 & \overline{H} \end{bmatrix} \begin{Bmatrix} \overline{\delta} \\ \overline{\phi} \end{Bmatrix} = \begin{Bmatrix} \overline{F} \\ \overline{P}_0 \end{Bmatrix} \quad \ldots (1)$$

where $\overline{M}$, $\overline{C}$, and $\overline{K}$ = mass, damping, and stiffness matrices of the structure, respectively, ρ = fluid density, $\overline{\delta}$ = nodal displacement vector, ϕ = velocity potential related to the pressure by $p = -\rho\frac{\partial\phi}{\partial t}$, D_{ij} = element of the fluid damping matrix, $\overline{D} = \frac{1}{c}\int_{\Gamma_\gamma} \overline{N}_i\overline{N}_j d\Gamma$, in which c = wave celerity, $\overline{N}_i$ and $\overline{N}_j$ = interpolation functions for the fluid elements, and Γ_r = radiation boundary at a distance, $x = \gamma$, $\overline{L}$ = coupling matrix = $\int_{\Gamma s} \overline{N}_i^T n \, \overline{N}_j d\Gamma$ in which n = unit vector normal to the face, and the integration is carried over the interface region, Γ_s, H_{ij} = element of the fluid stiffness matrix = $\int_{\Omega_f} (\nabla\overline{N}_i)^T(\nabla\overline{N}_j)d\Gamma$, in which R = seismic load vector, and P = vector due to the interface fluid pressure.

The boundary conditions are $\frac{dp}{dz} + (\frac{d^2p}{dt^2})\frac{1}{g} = 0$ at the free surface ...(a) where p = fluid pressure in excess of the hydrostatic value, z = coordinate in the vertical direction, and g = gravitational acceleration. $\frac{dp}{dz} = 0$ at the seabed ...(b), $\frac{\partial p}{\partial n} - \dot{s}_n - i\rho\omega\frac{\partial\phi_0}{\partial n} = 0$ at the structure-fluid interface...(c), where ϕ_0 = velocity potential of any incident wave, if present, and $\dot{s}_n$ = normal component of the structure velocity, $\frac{\partial p}{\partial x} + \frac{1}{c}\frac{\partial p}{\partial t} = 0$, the Sommerfeld radiation boundary condition...(d). Eqs. 1, which are unsymmetric, are solved by a step-by-step integration procedure.

2.2 Lumped Parameter Analysis: For the particular case of vertical ground motion, i) the linear finite element model is checked, and ii) the analysis extended to account for the nonlinear behavior of the water medium. The water medium is treated as a series of discretized masses, springs, and dashpots following the procedure outlined in Ref. 4. The connecting elastic spring stiffnesses are based upon the compressibility of the water, and the dashpots are assumed to provide 0.5% critical damping. The water column is assumed to act as an elastic bar with its vertical sides restrained against horizontal displacement - 'trapped' water model, Fig. 1. The nonlinearity is simulated by elastic bilinear springs, Fig. 2. The opening and closure of the gap provides for the cavitation effect.

3. NUMERICAL EXAMPLE: The example structure is a floating platform, similar to the Atlantic Richfield Company Liquid Petroleum Gas facility (ARCO-LPG) used in the Java sea at the Ardjuna field; the schematic is shown in Fig. 3 (Ref. 5). For the plane strain finite element analysis, the longgitudinal section of the prestressed concrete hull is idealized as an equivalent sandwich plate by 'smearing' the web members across the platform width. The loading is assumed to be a Taft earthquake input, with the vertical component acting at the seabed level, and the horizontal component at the mooring level. The mean square response value is determined, and the spectral band width obtained from the spectral moments. Extreme value statistics, based on the work of Cartwright and Longuet-Higgins (Ref. 6) is then applied to obtain the mean and standard deviation of the extreme response value.

4. ACKNOWLEDGEMENT: The authors would like to thank Dr. R. T. Dempster, Dean of Engineering, and Dr. A. A. Bruneau, Vice-President, Memorial University of Newfoundland, Dr. W. E. Russell, Director, Newfoundland Oceans Research and Development Corporation, and Dr. J. S. Tennant, Chairman, Ocean Engineering, Florida Atlantic University, for their continued interest and encouragement. The support of this investigation by National Research Council of Canada, Grant No. 8119, is gratefully acknowledged.

5. REFERENCES: 1) Reddy, D. V., Arockiasamy, M., Haldar, A. K., and Thangam Babu, P. V., "Response of an Offshore Floating Nuclear Plant to Seismic Forces", Proc. Conf. Vibration in Nuclear Plants, Keswick, U. K., May 1978. 2) Arockiasamy, M., Reddy, D. V., Thangam Babu, P. V., and Haldar, A. K., "Probabilistic Response of Floating Nuclear Plants to Seismic Forces", Proc. Fifth Nat. Meeting of the Univ. Council for Earthquake Eng. Res., M.I.T., 83-85 (1978). 3) Arockiasamy, M., Thangam Babu, P. V., and Reddy, D. V., "Probabilistic Seismic Fluid-Structure Interaction of Floating Nuclear Plant Platforms", Proc. Fifth Conf. on Struct. Mech. Reactor Tech., Berlin, K4/7 1-8 (1979). 4) Williamson, R. A., Kennedy, R. P., Bachman, R. E., and Chow, A. W., "Response of a Proposed Nuclear Powered Ship to Water-Transmitted Earthquake Vibrations", Technical Report, Nuclear and Systems Sciences Group, Holmes and Narver, Inc., 1975. 5) Reddy, D. V., Sodhi, D. S., Arockiasamy, M., and Haldar, A. K., "Response of An Offshore Floating LPG Storage Platform to Simulated Wind and Ice Forces", Proc. Fourth Int. Conf. on Port and Ocean Eng. under Arctic Conditions (POAC), St. John's, Nfld., Sept. 1977. 6) Cartwright, D. E. and Longuet-Higgins, M. S., "Statistical Distribution of the Maxima of a Random Function", Proc. Roy. Soc. (Series A), 237, 212-232 (1956).

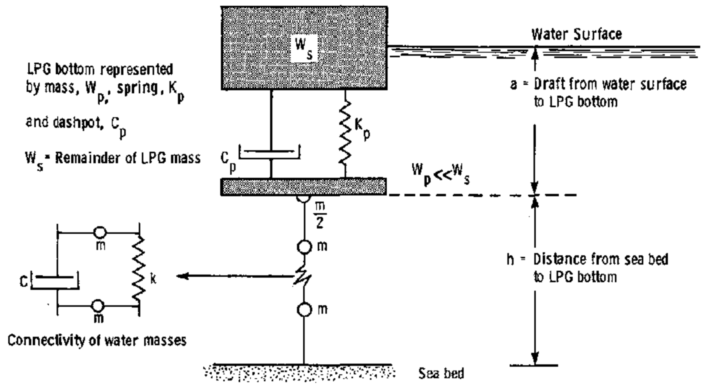


Fig. 1. ' TRAPPED' WATER MODEL (from Ref. 4)

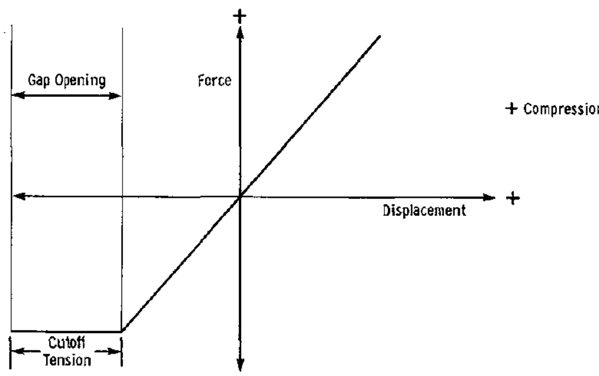


Fig. 2. NON LINEAR SPRING BEHAVIOR (from Ref. 4)

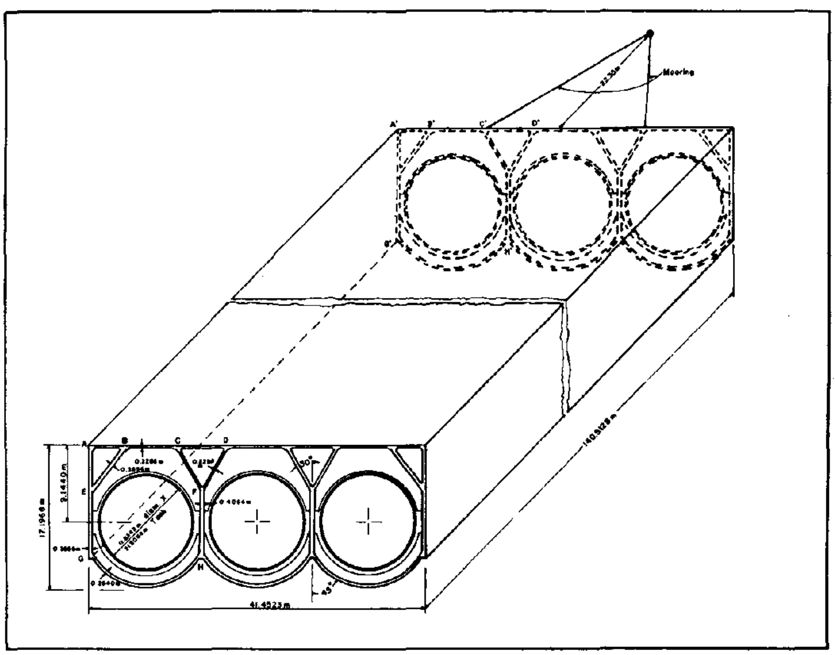


Fig. 3 SCHEMATIC OF THE LPG (from Ref. 5)

M. AROCKIASAMY
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, Newfoundland

D. V. REDDY
Ocean Engineering
Florida Atlantic University
Boca Raton, Florida

P. S. CHEEMA
College of Trades and Technology
St. John's, Newfoundland

1. INTRODUCTION: A dynamic non-stationary response analysis is presented for a three-dimensional framed offshore tower subjected to seismic nonstationary random excitation. Non-stationarity of ground motion significantly influences the structural response. A typical earthquake record is characterized by an initial build-up time, a period of relatively high uniform intensity, and a gradually decaying tail. Some of the non-stationary random time series methods developed for the construction of artificial accelerograms are: a) multiplication of a stationary random time series by a non-stationary envelope function, b) change in the frequency content of artificial accelerograms as a function of time, and c) superposition of available earthquake records with phase delays in time (Refs. 1, 2 and 3).

In this paper, the procedure described in Ref. 4 is used to treat the accelerograms as piece-wise separable, and estimate the frequency-independent modulating function by the mean square minimization criterion. The determination of the response of a multi-degree-of-freedom system to non-stationary excitation, using evolutionary covariance matrices, is based on the linear (state space) time domain formulation presented in Refs. 5 and 6.

2. THEORY

2.1 Evolutionary Power Spectral Density: A non-stationary process, $x(t)$, is said to be separable, or uniformly modulated for a nonnegative function, $c(t)$, and a covariance stationary process, $n(t)$, of zero mean and unity variance if $x(t) = \sqrt{c(t)}\, n(t)$ . . .(1). The covariance function and the evolutionary power spectral density of the separable process, defined in Eqn. 1, are respectively, $R_x(t,s) = \sqrt{c(t)\, c(s)}\, R_n(t-s)$ ...(2), and $f(t,\omega) = c(t)\, f_n(\omega)$...(3), where R_n and f_n are the stationary covariance function and spectral density of the process $n(t)$. For each section of the earthquake accelerogram, the frequency independent modulating function, $c(t)$, is determined applying the mean square minimization criterion, and the associated stationary process, $n(t)$, obtained from Eqn. 1. Using the standard approach outlined in Ref. 7, the power spectral density function, $f_n(\omega)$ of $n(t)$, is estimated and the evoluationary power spectral density of the motion computed at various times using Eqn. 3. Then, the instantaneous evolutionary spectral densities, $p(t,\omega)$ for three termination times, t_1, t_2 and t_3, of the accelerogram are

$$\begin{aligned} p(t,\omega) &= c_1(t)\, f_1(\omega), && t_0 \le t \le t_1 \\ &= f(t_1,\omega) + c_2(t) f_2(\omega), && t_1 \le t \le t_2 \\ &= f(t_2,\omega) + c_3(t) f_3(\omega), && t_2 \le t \le t_3 \qquad \ldots(4) \end{aligned}$$

2.2 Linear Formulation with Modal Decomposition: For a linear multi-degree-of-freedom system, the modal equation, assuming a scalar ground acceleration, $\ddot{Y}_g(t)$, as the excitation is of the form

$$\ddot{x}_i(t) + 2\xi_i\omega_i\dot{x}_i(t) + \omega_i^2 x_i(t) = -\Gamma_i\ddot{Y}_g(t), \quad \ldots(5)$$

in which Γ_i = the modal participation factor, and ξ_i = fraction of the critical damping. Eqn. 5 is written in linear (state) form as

$$\dot{\overline{x}}_i(t) = \overline{A}_i\ \overline{x}_i(t) + \overline{B}_i\ddot{Y}_g(t), \quad \ldots(6)$$

where $\overline{x}_i(t) = \begin{vmatrix} x_i(t) \\ \dot{x}_i(t) \end{vmatrix}$, $\overline{B}_i = \begin{vmatrix} 0 \\ -\Gamma_i \end{vmatrix}$, $\overline{A}_i = \begin{vmatrix} 0 & 1 \\ -\omega_i^2 & -2\xi_i\omega_i \end{vmatrix}$, and the state vector of modal responses is given by

$$\overline{x}(t) = \begin{vmatrix} \vdots \\ \overline{x}_i(t) \\ \vdots \end{vmatrix}, \; i = 1, \ldots n \quad \ldots(7)$$

The evolution of the covariance matrix of the state vectors, x_i, x_j, defining the modal responses $\Sigma_{x_i x_j}(t)$, is given by

$$\Sigma_{x_i x_j}(t) = \overline{\phi}_i(t)\Sigma_{x_i x_j}(0)\overline{\phi}_j(t) + \int^t \overline{\phi}_i(t-\tau)\overline{B}_i\ Q(\tau)\overline{B}_j^T\phi_j^T(t-\tau)d\tau, \quad \ldots(8)$$

where the transition matrix, $\overline{\phi}_i(t)$, is obtained from the homogeneous solution of the modal equation for a given initial displacement and velocity. An equivalent white noise is specified based on the evolutionary power spectral density, Fig. 1, as indicated in Ref. 8, and the strength function, Q(t), is treated as a piece-wise linear function.

3. NUMERICAL EXAMPLE: Multi-degree-of-freedom lumped mass modeling is used for the dynamic non-stationary analysis of a three-dimensional framed offshore tower, Fig. 2 (Ref. 6). The evolutionary power spectral densities for the N-S and E-W components of the 1934 El Centro earthquake, and the S-E and S-W components of the Olympia 1949 earthquake (Ref. 4) are used in the determination of the strength function. Fluid-structure interaction is considered in an approximate manner using the added mass concept.

4. ACKNOWLEDGEMENT: The authors would like to thank Dr. R. T. Dempster, Dean of Engineering, and Dr. A. A. Bruneau, Vice-President, Memorial University of Newfoundland, Dr. J. S. Tennant, Chairman, Ocean Engineering, Florida Atlantic University, and Mr. O. S. Toope, Academic Head, College of Trades and Technology, Newfoundland, for their continued interest and encouragement. The support of this investigation by National Research Council of Canada, Grant No. 8119, is gratefully acknowledged.

5. REFERENCES: 1) Amin, M. and Ang, A. H., Structural Research Series No. 306, Dept. of Civil Eng., Univ. of Illinois, 1966. 2) Goto, H., Toki, K., and Aiyoski, T., Proc. Japan Earthquake Engineering Symp. 25-30 (1966). 3) Jennings, P. C., Housner, G. W., and Tsai, N. C., Earthquake Engineering Research Lab., Calif. Inst. of Tech., Pasadena, 1976. 4) Liu, S. C., Bull. Seism. Soc. Am. Vol. 60, No. 3, 891-900 (1970). 5) Gasparini, D. A., Proc. ASCE, Vol. 105, No. EM1, 13-27 (1979). 6) Reddy, D. V., Arockiasamy, M., and Cheema, P. S., Proc. 5th Int. Conf. on Port and Ocean Engineering Under Arctic Conditions (POAC), Trondheim, Norway, 1979. 7) Liu, S. C. and Jhaveri, D. P., Bull. Seism. Soc. Am. 59, 1517-1534 (1969). 8) Bycroft, G. N., J. Eng. Mech. Div., ASCE, 86, No. EM2, 1-16 (1960).

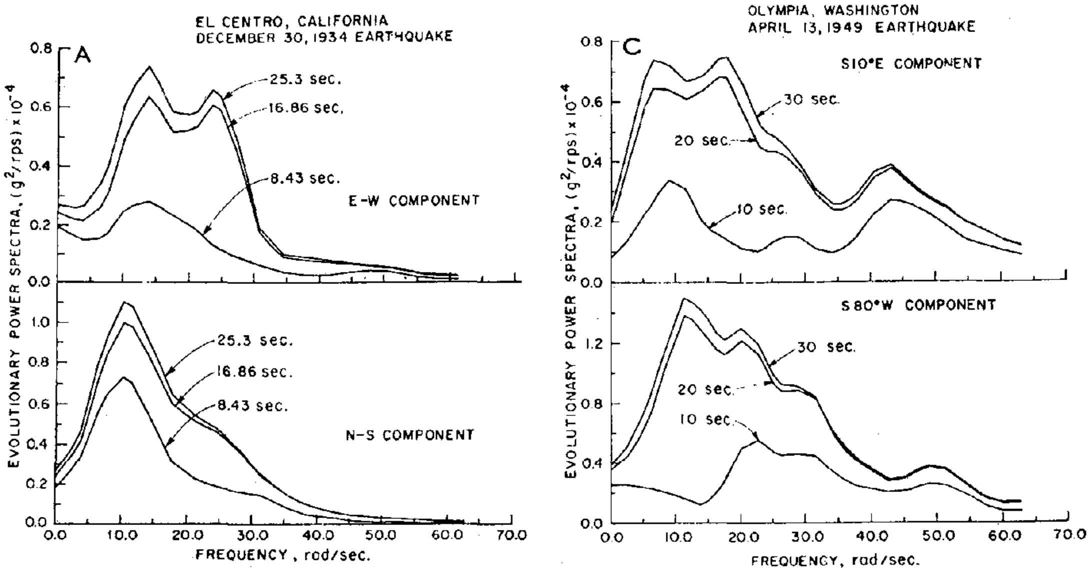
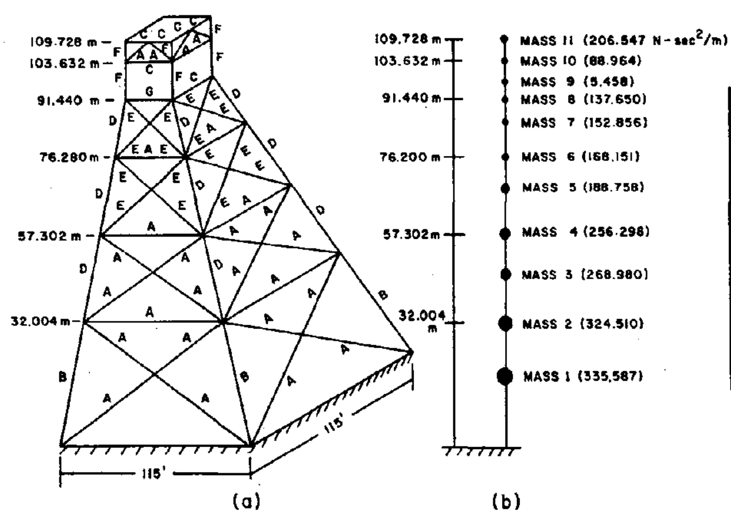


FIG.I. EVOLUTIONARY POWER SPECTRAL DENSITIES
(From Ref. 4)



MEMBER	CROSS-SECTIONAL AREA (m^2)	MOMENT OF INERTIA (m^4)
A	0.0208	0.0071
B	0.1540	0.0179
C	0.0465	0.0094
D	0.1205	0.0085
E	0.0188	0.0005
F	0.0750	0.0008
G	0.0167	0.0004

FIG. 2 THREE-DIMENSIONAL OFFSHORE TOWER AND LUMPED MASS MODEL
(From Ref. 6)

B. J. GOODNO, J. I. CRAIG, and K. M. WILL

Georgia Institute of Technology

Introduction

The interaction of light and heavyweight cladding systems with the primary structural frame under moderate seismic loading is under investigation in the Schools of Civil and Aerospace Engineering at Georgia Tech. The study involves a balanced combination of analytical and experimental investigations aimed at identifying the contribution of nonstructural cladding systems in the performance of modern highrise buildings. This study is sponsored by NSF through Grant ENV77-04269.

Analytical Studies

Results of recent work [1,2,3] have shown that computer simulation methods can be used to predict the dynamic properties and localized response of lightweight (i.e., glass) cladding systems to wind loading and earthquake-induced building frame distortions. In the case of heavyweight claddings (e.g., precast concrete), the curtain wall has been found to fulfill a limited structural role, altering ambient level vibration frequencies to a substantial degree and either increasing or decreasing overall structural response to moderate ground motion input [3].

Computer models are currently being assembled for two steel frame highrise buildings in the Atlanta area which are the subjects of ambient and forced vibration test programs. One is a 24 story steel frame office building of core construction with a heavy precast concrete facade. Analytical studies have resulted in development of finite element models of the primary structural frame, the lightweight exterior frame which supports the curtain wall, and the cladding panels themselves and their connections. The building model was calibrated on the basis of ambient-level vibration test results. The precast cladding model was added to the building model to obtain a match between measured and predicted structure frequencies. Addition of the cladding was found to alter structure frequencies appreciably, and to either increase or decrease peak displacement response to moderate base excitation depending on the relationship between overall structure frequencies and the frequency content of the input ground motions considered. These findings have demonstrated that it may not always be conservative to neglect cladding-structure interaction effects. Currently, the investigation is focusing on the influence of cladding on the torsional frequencies and response of the structure with heavyweight cladding.

Analytical and experimental investigations of a second structure with a reflective glass cladding have just been initiated. The 24 story steel frame building has braced framing in one direction and rigid framing in the other. The building is under construction at present and will be tested in its unclad, partially clad, and fully clad states for comparison with analytical predictions of dynamic properties at various stages of construction. The computer model of the structure is under development at the present time.

Experimental Studies

The experimental phase of the research is now fully underway. Measurements of full-scale structural response are being carried out at the two sites. In addition, construction is complete on a rectilinear vibration generator (RVG), and a series of tests are underway to verify its performance capabilities.

The building response instrumentation consists of five milli-g level accelerometers of the force-balance design (Kinemetrics FBA series). The complete response measurement system as currently configured consists of the accelerometers and custom designed signal conditioner along with a portable 8 channel FM tape recorder. The system and all cabling can be set up in a 25 story building within 2 hours so that it is possible to obtain 8-10 hours of continuous data during a one-day test.

The initial shakedown tests of the response instrumentation and the development of suitable and efficient test procedures were carried out at the heavily clad building. At the present time, a complete ambient level response survey has been made which includes bending response along both axes as well as torsion response and includes the first 3 modes in all cases. In addition, estimates of bending mode frequencies and damping for as high as the 5th mode have been obtained but not confirmed by mode shape measurements [2,3]. A comparison of bending response at two different levels of forcing (wind speed) has also been obtained. Mode shapes and properties were obtained by analysis of the cross power spectra and some limited single degree of freedom curve fitting. Work is currently underway on the development of both single and multi-degree of freedom curve fitting algorithms that can be applied to cross power spectra of the response measured at multiple locations.

The original research plan called for response measurements to be carried out on another building during construction and installation of the cladding. After lengthy, tedious and trying negotiations with the owner and general contractor, it became obvious that access to the structure would not be possible. The problem centered around a strong mutual distrust between the owner and the contractor and their unfounded fear that the proposed tests might somehow provide a basis for future lawsuits. Consequently, efforts were directed at finding another site and the result was selection of the glass-clad building. This is currently the only medium size steel frame building under construction in the area, and access was obtained without any difficulties. The two key disadvantages, however, are the relatively complicated structure and the lightweight cladding design. At the present time, a complete ambient level response survey which includes both torsion and two-axis bending response has been performed. The tests were carried out over a period of one month beginning shortly after the last floor slab was poured (no cladding installed) and ending with the cladding about 35% installed.

Design and construction of the RVG have been completed. Briefly, the key features of the unit are:

* Peak force levels to 5000 lbs. in a horizontal plane
* Maximum sinusoidal frequency of 10 Hz at 5000 lb. force level
* Overall performance equal to or better than Kinemetrics VG-1
* Rectilinear operation using servocontrolled hydraulic actuator
* Steady state or transient operation using arbitrary forcing functions.

The unit employs a seismic mass of up to 3000 lbs. which is supported on four large air bearings and driven in a rectilinear fashion by a small high-pressure servocontrolled hydraulic actuator. A thick base plate over which the air bearings ride provides a suitable working surface and spreads the static weight of the unit so that the direct floor loading is less than 150 lbs. per sq. ft. The actuator is attached to the base plate in a manner allowing simple rotational adjustment so that the force vector can be aligned in any horizontal direction. The unit is supported by a 10 gpm hydraulic power supply and a small air compressor.

Preliminary testing revealed instabilities in the air bearings and after several redesigns this problem appears to have been resolved. Laboratory tests are currently underway to verify performance. A series of shakedown tests of the RVG are planned for a small building on campus during April and May. Following this the unit will be used to carry out forced response tests in both buildings.

Conclusions

Analytical and experimental studies of cladding performance are limited to the linear range in these initial studies aimed at investigation of cladding-structure interaction effects in modern buildings. The goal of the study is to increase the understanding of cladding behavior in modern building construction so that rational procedures for its design, perhaps as a lateral stiffening element to control low-level building motions, can be developed in the future.

References

1. Will, K. M., Goodno, B. J., and Saurer, G., "Dynamic Analysis of Buildings with Precast Cladding," Proceedings, ASCE Seventh Conference on Electronic Computation, held at Washington University, St. Louis, Missouri, August 6-8, 1979, pp. 251-264.

2. Goodno, B. J., Will, K. M., and Craig, J. I., "Analysis of Cladding on Tall Buildings," presented at the ASCE National Convention and Exposition, held in Atlanta, Georgia, October, 1979 (Meeting Preprint No. 3744).

3. Goodno, B. J., and Will, K. M., and Palsson, H., "Effect of Cladding on Building Response to Moderate Ground Motion," to be presented at the Seventh World Conference on Earthquake Engineering, to be held in Istanbul, Turkey, September 8-13, 1980.

J. N. YANG

The George Washington University

This paper summarizes current research at the George Washington University in the area of stochastic response of tall building to earthquake excitations sponsored by the National Science Foundation. The objective of this research program is to investigate (i) the effect of coupled lateral-torsional vibration resulting from building eccentricity, (ii) the use of transfer matrix technique in random vibration analysis of tall buildings, (iii) the difference and its significance between stationary and nonstationary random excitations in earthquake engineering applications, and (iv) the effect of multi-dimensional earthquake excitations on structural response and reliability.

Traditionally, structural dynamic problems are formulated in terms of normal modes of vibration, and the treatment of earthquake excited structures is no exception. The inclusion of the torsional degrees of freedom increases the number of modes and thus increases tremendously the amount of computation. This is especially true when torsional and translational motions are coupled. Unfortunately, uncoupled torsional and translational motions exist only if the mass center and the elastic center coincide for every story of the building, and if they lie on the same vertical line throughout the entire building. Therefore, coupled motions are normally expected and uncoupled ones are exceptions.

The importance of torsional motion in building response has been substantiated experimentally [1]. It was shown [1] from the analysis of records obtained during Feb. 9, 1971 San Fernando earthquake that the contribution of the torsional modes was indeed significant. Recognizing the importance of the torsional motion in the building response on the one hand and the complexity of a detailed analysis on the other, Kan and Chopra [2, 3] have proposed recently an approximate method to deal with a special class of building where the locations of the mass and elastic centers, while not necessarily coincident, are the same for every floor. The approach taken in [2,3] is essentially deterministic in nature, whereas the nonstationary random vibration is emphasized in the present program.

Actually, the most time consuming part of the traditional normal mode approach is in the determination of the normal modes. Yet, the knowledge of these modes is but an intermediate step toward the final goal which is the total structural response in terms of either deflections or forces. A logical alternative is clearly one which will dispense with this tedious intermediate step and reach directly to the goal. Such an analysis is indeed possible by a transfer matrix formulation in the frequency domain as presented in [4]. However, the transfer matrix approach can also be used to compute the normal modes and natural frequencies if so desired. Furthermore, it has the additional advantage of modeling the effects of damping locally and more realistically at different parts of the structure, whereas in a normal mode approach damping coefficients for different modes must be assumed based upon the analyst's experience and possibly test results, since the normal modes are those associated with an undamped structure.

The transfer matrix formulation is found to be most suitable for tall buildings where an elastic center and a mass center are identifiable for each story of the building. It is especially efficient if every story is identically constructed, or if the entire building is composed of several identically constructed sections [4]. Using the transfer matrix technique the computer time spent for computing the frequency response function was found to be only a small fraction of what would have been required if other analytical methods, such as the modal analysis, were used. Furthermore, very little additional computer time and no additional computer storage are needed if the number of stories is increased, as long as they are identically constructed [4].

It was found [4] that a moderate degree of eccentricity causes only a slight change in the level of response in the same direction as that of the ground motion, but its most significant effect is manifested by the response in the transverse direction and in torsion. For example, the base shear in the y direction induced by a ground motion in the x direction is about 40% of the base shear in the x direction. Therefore, the coupling effect should not be overlooked in the structural response analysis.

Structural response has been computed for two ground excitation models. The first model is a stationary process, and the second model is a non-stationary process. The nonstationarity in the second model is associated with a time-varying intensity which increases from zero to a peak level equal to that of the first model, and then diminishes again to zero. The maximum standard deviation of the structural response computed for the nonstationary excitation is found to be smaller than that of the stationary response under the stationary excitation, the difference being greater either when the damping ratio is lower, or when the fundamental frequency of the structure is lower. Therefore, the more elaborate and realistic nonstationary excitation model should be used in such cases.

REFERENCES

1. Hart, G. C., et al., "Torsional Response of High-Rise Buildings," J. Structural Divi., ASCE, Vol. 101, No. ST2, 1975, pp. 397-416.

2. Kan, C. L., and Chopra, A. K., "Elastic Earthquake Analysis of a Class of Torsionally Coupled Buildings," J. Structural Divi., ASCE, Vol. 103, No. ST4, 1977, pp. 821-838.

3. Kan, C. L., and Chopra, A. K., "Effects of Torsional Coupling on Earthquake Forces in Buildings," J. Structural Divi., ASCE, Vol. 103, No. ST4, 1977, pp. 805-819.

4. Yang, J. N., Lin, Y. K., and Sae-Ung, S., "Tall Building Response to Earthquake Excitation," paper to appear in Journal of Engineering Mechanics Division, ASCE, 1980.

W. J. Hall, N. M. Newmark, A. R. Robinson
D. A. W. Pecknold, W. H. Walker and D. A. Foutch

Department of Civil Engineering
University of Illinois at Urbana-Champaign
(NSF Grant No. ENV 77-07190)

The goal of the research program is to develop simplified methods of design of building structures to resist dynamic loads arising from natural hazards such as earthquakes and, to a lesser extent, wind. The research emphasizes the development of new and improved methods of analysis. Work is underway in three interrelated areas as follows: (1) simplified methods of analysis and design for excitation arising from earthquake and wind; (2) response of subsystems to dynamic motions; (3) design of multi-degree-of-freedom systems with special attention to inelastic behavior. The graduate student and professor investigating each phase of the project are indicated. The project will be finished on 30 April 1980; studies on many subtopics have been completed, and many summary reports and papers have been prepared and are available upon request.

Simplified Methods of Analysis and Design

The response of elasto-perfectly-plastic systems combined with various damping levels is being analyzed with the purpose of assessing the reliability of inelastic design spectra currently used. Earlier studies were aimed at developing an empirical amplification factor versus damping relationship valid over a wide range of damping values (R. Riddell -- Prof. N. M. Newmark).

This soil-structure interaction study involved consideration of the analysis of earthquake records in a manner to account for wave dimensions and building size as they affect lateral and torsional motions. A numerical averaging approach applied to free field records has proven useful in estimating the effect of building size on response (J. R. Morgan -- Prof. W. J. Hall and Prof. N. M. Newmark).

One research topic is being carried on in the general area of modeling of buildings and soil-structure interaction. This investigation involves study of the frequency dependence of foundation parameters and of techniques for handling nonclassical damping, in a manner to permit single calculation of interaction effects (K-Y. Shye -- Prof. A. R. Robinson).

Another study deals with vertical acceleration and its influence on P-Δ effects accompanying lateral motion. The nonlinear coupling of lateral modes also is being considered. Ranges of significance for pertinent parameters and design recommendations are being sought which adequately account for the effects of vertical acceleration coupled with lateral motion and including the nonlinear coupling of lateral modes (A. C. Stepneski -- Prof. A. R. Robinson).

A continuation of studies of the design and behavior of low-rise steel frame buildings is underway with particular attention to the resistance offered by floors (F. Cotran -- Prof. W. J. Hall) and resistance offered by infilled walls (C. E. Rivero -- Prof. W. H. Walker). In these studies, special attention will be given to reserve strength and techniques for handling such elements in dynamic response calculations.

A new study involves development of some simple physical models that can be employed in studying nonlinear behavior of simple systems and some special aspects of ground motions. The studies initially will be theoretical in nature, hopefully followed by limited testing of models at a later date (J. M. Nau -- Prof. W. J. Hall).

Two topics dealing with wind loads on structures have been under study. One is an investigation into the feasibility of using a unified design procedure to account for the dynamic effects of earthquakes and wind loads in buildings. In addition to investigating the commonality of analysis approaches the study involved development of a wind response spectrum, similar to that employed for earthquakes (P. Cevallos-Candau -- Prof. W. J. Hall). Another wind-related study is concerned with the effects of variable direction of the wind on the lateral and torsional response of buildings. A major goal is to provide analysis methods suitable to the design office (E. Safak -- Prof. D. A. Foutch).

A final topic under study in this area involves interaction between buildings and developments of techniques for handling differential motions (F. Castilla -- W. H. Walker).

Response of Subsystems to Dynamic Loads

A study of tuned secondary systems utilizing concepts in classical dynamics and applied mathematics has three goals: the development of numerical procedures for accurate computation of secondary response; the attainment of a qualitative understanding of secondary response phenomena; and the development of techniques for obtaining fast but reliable secondary response estimates (G. C. Ruzicka -- Prof. A. R. Robinson).

A second study involved formulation of approximate methods of predicting the maximum response of single and multi-degree-of-freedom secondary systems with single or multiple attachments to a multi-degree-of-freedom primary system (R. Villaverde -- Prof. N. M. Newmark).

Design of Multi-Degree-of-Freedom Systems

One study is aimed at deriving an approximate method of analysis for nonlinear multi-degree-of-freedom systems. The method is an iterative one which utilizes only elastic response spectra and elastic modal analysis techniques. The mode shapes and frequencies of the elastic system are adjusted to account for the nonlinear behavior (V. Tansirikongkol -- D. A. W. Pecknold). A second study involves study of the effect of variation of ground motion parameters on the response of complex structures (S-Y. Kung -- Prof. D. A. W. Pecknold).

Y. K. LIN and TENG-YUAN SHIH

University of Illinois at Urbana-Champaign

Introduction

It is now a common practice to model earthquake ground motions as stochastic processes, and to treat the structural response as a random vibration problem, in recognition of the fact that the occurence of future earthquakes, their magnitudes and wave forms are not predictable in advance. The present research project seeks to utilize recent advances in the theory of stochastic processes in this particular area of application, with special emphasis on the effects of vertical ground acceleration.

For vertically erected structures, the horizontal ground motion gives rise to external excitations, in the sense that they appear as inhomogeneous terms in the governing equations. In contrast, the terms associated with the vertical ground motion appear in the coefficients of the governing equations; they are called internal or parametric excitations which cause the characteristics of a dynamic system to vary with time.

Published analytical studies related to parametric excitations are mostly concerned with the stability of system response. When the excitations are stochastic, the objective of an investigation is usually the asymptotic stability in a suitable statistical sense. However, since strong motion earthquakes are generally short, lasting somewhere between several seconds to one or two minutes, the asymptotic stability solution has little practical significance in earthquake engineering applications. The more important aspect of parametric excitations in this case lies in their ability to enhance the power of the non-parametric external excitations; namely, the presence of vertical ground acceleration can cause greater structural response than if the horizontal ground acceleration were to act alone.

Analysis

A simple structural model chosen for preliminary study consists of a massless beam-column which is supporting a concentrated mass at the top and is clamped in the ground at the lower end. If the column material is linearly elastic, the equation of motion can be written as follows:

$$\delta_{tt} + 2\zeta\omega_o\delta_t + \omega_o^2\left(1 - \frac{mg}{P_{cr}} - \frac{m}{P_{cr}} v_{tt}\right)\delta = - u_{tt} \qquad (1)$$

in which ω_o and ζ are the usual symbols for the natural frequency and the damping ratio, u and v are the horizontal and vertical ground motions, and each subscript t denotes a time-differentiation. The horizontal and vertical ground accelerations are idealized as modulated white noise processes; i.e., each is a white noise multiplied by a deterministic non-negative envelope function which increases from zero to a maximum level of unity and then reduces again to zero. Under such excitations, the structural response, represented as a vector in the phase plane, is a Markov vector. The statistical properties of the response can then be computed using known mathematical methods available for the Markov stochastic processes (see, e.g. 2, 3, 4).

The time-dependent mean-square value of the structural displacement is computed for the case when the horizontal ground acceleration is acting alone, and for the case when both the horizontal and the vertical ground motions are present. In the latter case, the spectral level ratio between the vertical ground acceleration and the horizontal ground acceleration is assumed to be 0.64. The effects of the vertical ground acceleration is found to be greater for greater initial response (i.e., the mean-square response initially computed without taking the vertical ground motion into account). However, within the elastic range the percent increase in the structural response is found to be negligible. These results, in addition to showing the general trend of the effects of the vertical ground motion, indicates the need for a nonlinear inelastic structural model for the analysis.

A hysteresis model originally proposed by Hata and Shibata (5) can be modified to include the parametric excitation as follows:

$$X'' + 2\zeta X' + (r-K_2)X + (1-r)\ \mathrm{sgn}\ X' = -U + K_1 V''X \qquad (2)$$

In this equation the structural displacement δ, and the horizontal and vertical ground motions u, v have been normalized with respect to the elastic limit δ_e, i.e., $X = \delta/\delta_e$, $U = u/\delta_e$, $V = v/\delta_e$. Each prime denotes one differentiation with respect to the dimensionless time $\tau = \omega_o t$. K_1 and K_2 and r are constants. It is of interest to note that the term associated with K_2 accounts for the P-δ effect due to gravitation alone, and the term associated with K_1 is the parametric excitation. Thus, each of the two effects can be discounted by setting either K_1 or K_2 to zero.

Time histories of the mean-square displacement response have been computed for two excitation levels. Some highlights are given in the following table:

TABLE I

Excitations	U	U-G	U-G-V
Peak Mean-Square Response	5.92	7.14	7.46
	22.4	28.8	32.9
Residual Mean-Square Response	4.74	6.43	6.68
	12.6	23.1	25.5

U-horizontal ground acceleration, G-gravity, V-vertical ground acceleration

These results show that the effects of vertical ground acceleration are not negligible, contrary to the conclusion obtained previously by Tani and Soda (6). It is possible that the discrepancy is due to the fact that in Ref. 6, the correlation between the output process X and the parametric excitation V" was not taken into consideration.

Acknowledgment

The research is supported by the National Science Foundation under Grant NSF PFR-7919619. Opinions, findings, and conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of National Science Foundation.

References

1. Lin, Y. K. and Shih, Teng-Yuan, "Column Response to Vertical-Horizontal Earthquakes," to appear in the Journal of Engineering Mechanics Division, ASCE.

2. Itô, K., "On Stochastic Differential Equations," Memoris of the American Mathematical Society, Vol. 4, 1951, p. 51.

3. Stratonovich, R. L., "A New Representation for Stochastic Integral and Equations," Journal of SIAM Control, Vol. 4, No. 2, 1966, pp. 362-371.

4. Arnolds, L., Stochastic Differential Equations: Theory and Applications, John Wiley, New York, 1974.

5. Hata, S. and Shibata, H., "On the Statistical Linearization Technique for Memory Type Nonlinear Characteristics," Control Engineering, Vol. 11, No. 10, 1956 (in Japanese).

6. Tani, S. and Soda, S., "Vertical Load Effect on Structural Dynamics," Proceedings, 6th World Conference on Earthquake Engineering, 1977, pp. 1028-1033.

Y.K. Wen

University of Illinois at Urbana-Champaign

This research is conducted as part of a continuing study of safety evaluation of structures to earthquakes and other natural hazards sponsored by National Science Foundation under grand No. ENV 77-09090.

This paper summarizes the latest developments in (1) analytical modeling of hysteretic restoring forces and multi-degree of freedom inelastic structures, (2) approximate analytical methods for the random response analysis and (3) study of sensitivity of response variables to system parameter uncertainties and lifetime reliability of structures against earthquake. Details are available in Refs. 1, 2, and 3.

Modeling of Hysteretic Forces and Multistory Structures

The smooth hysteretic restoring force model based on a differential equation was generalized to include effect of system degradation. The degradation can be in the strength (ultimate restoring force), the stiffness or both, and is a function of total hysteretic energy dissipated. The total energy dissipated is also of interest in its own right. It may be used as a more meaningful measure of structural damage or failure, than traditional maximum response or ductility factors, since a structure may be weakened more by stress reversals than a single large stress excursion.

Shear beam, rigid column-flexibile beam and discrete hinge models for multistory buildings were investigated. In the first two models, yielding and hysteresis are confined in the columns or beams therefore are suitable for structures with strong girder or strong column design, respectively. The discrete hinge model allows inelastic response in both beams and columns at the joints, therefore is a more reaslistic model. It is believed to be the first attempt of using this model in analytical study of random response of multistory inelastic structures.

Approximate Response Analysis

The inelastic system is linearized by minimizing the mean square errors. All system coefficients are obtained in simple closed form. Ordinary differential equations for the response covariance matrix is then obtained which reduce to algebraic equations for stationary solution and can be integrated numerically for nonstationary solution. The power spectral density function of the linearized but nonselfadjoint system is obtained by an eigenvalue analysis, from which first passage time and maximum response probability studies are also carried out. The accuracy of the solution procedure is verified by extensive Monte-Carlo simulations. It is found that the method gives very accurate covariance matrix and total energy dissipation however, has a tendency of underestimating the maximum response when there is significant yielding in the system. This is apparent due to the fact that at the extreme tail, the probability structure deviates significantly from the Gaussian law used in the analysis. Nevertheless, maximum response at the 50 percentile level is still satisfactory and can be used in safety analysis. Non-Gaussian procedures for the prediction of the maximum repsonse are presently being studied.

The results also indicated that the discrete hinge model provides significantly more insight into the response than do simpler shear beam or rigid column-flexibile beam models. Particularly, the detailed energy dissipation statistics at the critical joints of the structure derived from such model provide quantitative information for forumlation of more realistic criteria for structural damage or failure.

Sensitivity and Uncertainty Study

The methods developed allows one to evaluate the response statistics with more computational efficiency (compared with Monte-Carlo method) given the ground excitation intensity, frequency content (power spectral density) and structural resistance (system parameters). To evaluate the lifetime probability of failure of the systems, the uncertainties in both the excitation and the structural system parameters (e.g. earthquake intensity and duration, restoring force strength, post-yielding stiffness, hysteresis loop shape, etc.) need to be taken into consideration. For this purpose, a sensitivity study of the response (e.g. ductility) to system parameter variation is carried out. The effects of parameter uncertainties are incorporated through a first-order analysis, i.e.

$$\Delta_y^2 \simeq \sum_{i=1}^{N} C_i^2 \, \Delta_{x_i}^2 + \delta_y^2$$

in which Δ = total uncertainty, coefficient of variation
y = response variable of intent, e.g. ductility
x_i = system parameters, e.g. strength, post-yielding stiffness
$C_i = \frac{\partial y}{\partial x_i}(x_1, x_2 . \; . \; . x_n)]$ at $x_j = \mu_{x_j}$ in which μ_{x_j} = mean value of x_i. C_i is determined from the sensitivity analysis.
δ_y = the uncertainty (coefficient of variation) due to random oscillation of the system

The lifetime probability of failure (e.g. given ductility level y_d being exceeded) is therefore

$$P_f \simeq \int P(Y > y_d \mid I=i) \, f_I(i) \, di$$

in which I = lifetime maximum intensity.

References

1. Wen, Y.K., "Equivalent Linearization for Hysteretic Systems Under Random Excitation," Journal of Applied Mechanics, Trans., ASME, Vol. 46, December 1979.
2. Baber, T.T. and Wen, Y.K., "Equivalent Linearization for Hysteretic Structures," proceedings, ASCE, Engineeirng Mechanics Division Specialty Conference on Probabilistic Mechanics and Structural Reliability, Tucson, Arizona, pp. 25-29.

3. Baber, T.T. and Wen, Y.K., "Stochastic Equivalent Linearization for Hysteretic, Degrading, Multi-story Structures," Civil Engineering Studies, SRS No. 471, University of Illinois, Urbana, Illinois 1980.

C. N. KOSTEM and J. W. TEDESCO

Lehigh University

The reported research is aimed at determining the effect of the discrete connection points on the vibrational characteristics of shallow circular cylindrical tanks and examining the stress fields developed in the immediate vicinity of these discrete connection points, which anchor the tank to the rigid base when subjected to dynamic excitations. The forces exerted on the structural system are due to the horizontal ground motion. Fluid-tank interaction is included.

Earthquake Response of Shallow Tanks

Thin walled shallow circular cylindrical steel tanks are being extensively used in the petroleum and chemical industries. Tanks having a height (H) to diameter (D) ratio (H/D) of approximately 1.00 or less are designated as shallow tanks. The analytical research on the determination of the vibrational characteristics, tank-foundation interaction, and the earthquake response have been carried out for these tanks having uniform support conditions along the perimeter of their base. However, in practice the majority of cylindrical liquid storage tanks have been anchored to their base at discrete points along the perimeter of the tank shell wall. In the case of seismic disturbances, the transmittance of the forces between the tank and the base will primarily be through these anchors. The type of support of the shells at discrete points necessitated the use of a methodology which can accommodate the envisioned support conditions. It was decided to employ finite element method for the research [1].

Completed Preliminary Investigations

Prior to the initiation of the main body of the research it was decided to conduct two pilot programs to gain a better understanding of the dynamic behavior of shallow shells, and sensitivity of such behavior to finite element discretization. By using flat shell elements, empty tanks were discretized and fundamental frequencies of vibration were computed [1,3]. The purpose of the study was to determine the effects of mesh size on the correct assessment of the frequencies of vibration and the associated modal shapes. The second phase dealt with the development of a data base for the frequency of vibration of shallow cylindrical tanks of various heights and diameters with uniform support conditions at the base. All these tanks were designed in accordance with the current API Specifications and were analyzed by program KSHEL [2,5]. Results have provided a very simple technique and a table to predict the fundamental frequency of empty tanks [4].

Non-uniform Support Conditions

Stress concentrations developing at the vicinity of anchorage points will be analytically determined by using finite element method. The analysis will be conducted for empty, full and partially filled tanks. The ground excitation will be inputted via appropriate response spectrum. The modal superposition technique will be used to determine the dynamic response. It is expected that a second set of finite element analysis, through the use of substructuring, will have to be employed to determine the peak value of the stresses at the anchorage details. A limited parametric study will also be conducted to determine the effects of the changes in the dimensions of anchorage details on the stress concentration.

References

1. Bathe, K.-J., Wilson, E. L. and Peterson, F. E., "SAP IV A Structural Analysis Program for Static and Dynamic Response of Linear Systems," Earthquake Engineering Research Center Report No. 73-11, University of California, Berkeley, CA., 1974.

2. Kalnins, A., "KSHEL, Computer Program for the Analysis of Plates and Shells," Lehigh University, Bethlehem, PA., 1978.

3. Kostem, C. N. and Tedesco, J. W., "On the Accuracy of Finite Element Analysis of the Vibrational Characteristics of Shallow Cylindrical Tanks," Proceedings of the World Congress on Shell and Spatial Structures, IASS, Madrid, Spain, 1979.

4. Kostem, C. N. and Tedesco, J. W., "Vibrational Characteristics of Shallow Cylindrical Tanks," Proceedings of the 7th World Conference of Earthquake Engineering, Istanbul, Turkey, 1980.

5. API Standard 650-Welded Steel Tanks for Oil Storage, Seventh Edition, American Petroleum Industry, Washington, D.C., 1979.

BARRY J.S. LIU
ROBERT H. KIRCHHOFF
WILLIAM A. NASH

University of Massachusetts, Amherst, MA 01003

The problem of liquid sloshing against the dome of a slab-supported circular cylindrical liquid storage tank subject to seismic excitation is addressed from an experimental standpoint, guided by dimensionless analysis. To that end the Buckingham π-theorem is employed. To accomplish this, the random nature of a typical earthquake accelerogram is first considered and the power spectral density determined. The area under the spectral curve has been shown by previous investigators to be related to the second moment (or mean square value) of the process. It is reasonable to regard the frequencies at which these peaks occur to be the predominant frequencies. One of the characterizations of this type of random process is the RMS value. The time duration of the earthquake is another significant variable. The geometric shape and specific size of the container are also factors which influence the response of the system. Young's modulus and the density of the shell as well as liquid viscosity which accounts for wave decay in the liquid, and the liquid density are also to be considered. Finally, some inherent characteristics of the system, for example, the natural frequencies of the elastic tank and of the liquid, and the acceleration of gravity are also introduced as primary quantities in the analysis.

In this manner the generalized properties of this physical problem can be represented by seventeen variables in dimensionless form. These seventeen are in terms of the three fundamental variables mass, length, and time. Thus, the minimum number of groups required to relate the total variables becomes fourteen.

A series of experiments was carried out on sloshing in transparent domed, cylindrical tanks subject to base motion. Patterns of liquid impingement on the dome were determined together with dimensionless pressure parameters. It was found that the liquid response, as measured by either the wave height or hydrodynamic pressure against the dome is small compared to static pressure in the cylindrical portion of the tank unless the frequency of harmonic motion of the tank base is close to the first resonant frequency of the system consisting of the tank and contained liquid. At higher modes, sharp tuning is required to excite the liquid.

P. MUELLER and J.M. BECKER

Massachusetts Institute of Technology

The research reporeted in this paper forms part of the project "Seismic Resistance of Precast Concrete Panel Buildings" that is being carried out at the Massachusetts Institute of Technology under the sponsorship of the National Science Foundation. Principal Investigator is Prof. James M. Becker.

Precast concrete panel buildings are bearing wall systems, in which usually both the structural walls and the floors are prefabricated. Both precast wall panels and floor planks are joined on site by various connection details. Present construction practice, which has mainly developed in non-seismic regions, often results in systems in which the connections represent the weakest structural elements. The connections represent therefore both a serious problem and a challenge in aseismic design of such buildings. Two basic lateral load resisting elements can be distinguished in panelized buildings: simple walls and composite walls. Simple walls have only horizontal, composite walls have both vertical and horizontal connections. Research efforts have been directed towards three major areas:

(1) Seismic Behavior of Simple Walls. This study concentrates on the effects of horizontal connection behavior on seismic response.

(2) Seismic Behavior of Composite Walls. This study concentrates on the effects of vertical connection behavior on seismic response and is described in more detail below.

(3) General Response of Precast Concrete Panel Buildings. This study investigates 3-D behavior, effect of floor diaphragms, solid-structure interaction, non-simultaneous base excitation, etc.

Seismic Behavior of Precast Composite Walls.

This study consists of three efforts

- Evaluation of alternative aseismic design concepts.

- Investigation of the seismic behavior of structural walls coupled through vertical connections or coupling beams.

- Tests on the cyclic behavior of vertical connections.

Alternative Aseismic Design Concepts.

Precast composite walls have both vertical and horizontal connections. Because these connections often represent the weakest structural elements, in which the primary inelastic action occurs, composite walls can be viewed as structural systems with localized nonlinearity and inelasticity. This suggests to investigate a design approach that is used in the New Zealand Code.

In the capacity design approach of the New Zealand Code primary energy dissipating mechanisms are chosen. The primary energy dissipating elements that participate in the mechanism, are suitably designed and detailed, and all other elements are then provided with sufficient reserve strength capacity to ensure that the chosen energy dissipating mechanisms are maintained throughout the deformations that may occur . In this sense a major concern of aseismic design concepts is the establishment of favorable hierarchies of yield mechanisms . Based on a review of the literature, codes and past earthquake experience, criteria are being developed that characterize favorable primary energy dissipating yield mechanisms. Using these criteria, the merits and shortcomings of different aseismic design concpets are evaluated. Based on the observation that coupled shear walls, excentrically braced frames and composite walls all basically represent cantilevers with weak longitudinal fibres, it was concluded that directing the primary inelastic action into weak, but tough vertical connections represents a promising alternative to the usual design approach attempting monolithic behavior of composite walls.

Seismic Behavior of Structural Walls Coupled Through Vertical Connections or Coupling Beams.

Vertical connections in composite walls play basically a similar role as coupling beams in coupled structural walls. Using coupling elements (vertical connections, coupling beams) as primary energy dissipating elements raises in both cases the question which coupling stiffness and strength relative to that of the walls will lead to the best energy dissipation characteristics of the structure. This question is addressed in a series of parametric computer studies. An effort is made to present results on the optimum coupling strength and stiffness in a form that is independent of a specific wall configuration or specific coupling elements (vertical connections, coupling beams).

Tests on the Cyclic Behavior of Vertical Connections

Precast concrete panel buildings typical of North American practice often use embedded welded or bolted metal details for vertical connections. Such vertical shear connectors appear also most promising in connection with an aseismic design concept that uses vertical connections as primary, energy dissipating elements. However, only very limited test results on vertical shear connectors exist. An experimental program on the hysteretic behavior of vertical shear connectors under cyclic loading has therefore been initiated and is carried out in the laboratories of Wiss, Janney, Elstner and Associates, Inc. under the direction of Prof. J.M. Becker. The primary objective is to investigate the behavior of shear connectors typical of current design practice. However, dependant on the results, it is also intended to test some innovative solutions for tough vertical shear connectors.

W. O. KEIGHTLEY

Montana State University

Digital computer studies of 20-story buildings containing auxiliary Coulomb friction dampers are being conducted to determine the properties which the dampers should have to minimize building response. Laboratory work is underway to develop practical dampers which can be installed in buildings. The National Science Foundation has funded this work for 2 years; continued support is being sought.

Digital Computer Studies

A class of 20-story structures having fundamental periods varying from 0.5 sec. to 5 sec. was created by multiplying all floor masses of a basic building by appropriate constants, elastic properties remaining unchanged. Within the frames, diagonal Coulomb damping struts connect each floor to the floor below. The dampers are characterized by 2 properties: elastic stiffness when not slipping, and magnitude of slip force. These properties give the dampers an elastic-plastic force-deflection characteristic; the combination of structural frame and dampers together has a piecewise linear hysteretic characteristic. Damper stiffness in each story is equal to a constant, STFCON, times the stiffness of the frame against shearing deformation of that story. The slip force in each story's damper is equal to a constant, F/W, times the building's weight above that story. Both constants are held uniform throughout all stories so that a building is classified by 3 numbers: the fundamental period, T_1; STFCON; and F/W. Response to the El Centro record was computed for numerous combinations of these constants, enabling response spectra to be plotted. Figs. 1(a), (b) are examples of spectra.[1]

The spectra showed that there are combinations of F/W and STFCON, depending on T_1, which result in minima or near minima of most response parameters. In general, the stiffer the dampers, the smaller all responses. Optimum F/W depends on T_1 and to a lesser extent on STFCON. For $T_1 = 5$ sec., least response occurs when F/W = 0.02; for $T_1 = 2$ sec., F/W = 0.06; and for $T_1 = 0.75$ sec. optimum F/W should be at least 0.20. With these optimum damper properties, response to El Centro is about the same as would be produced by 10% to 20% critical viscous modal damping in all modes. Doubling the earthquake intensity produced more than doubled response when F/W was small and less than doubled response when F/W was large. These results can be qualitatively explained by the fact that as well as absorbing energy, the dampers stiffen a frame and thus shift the fundamental period toward the dominant period of the ground motion. Postearthquake residual displacements were negligible.

Findings to date indicate that modest damper forces can significantly reduce earthquake induced forces, deformations, and accelerations of many structures. Also suggested is that some building frames be made less stiff, perhaps through flexible joints, and then be modified by adding energy dissipators. A wider range of ground motions and frames must be studied, and economics must be considered before the latter statement can be made as a recommendation.

A Telescoping Friction Damping Strut

A telescoping friction damping strut which has been developed consists of 2 pieces of steel tube surrounded by 1/4" thick steel plates which are pressed against it by spring loaded clamps. Alternate plates connect to opposite ends of the tube. As the tube changes length, energy is consumed through friction by the plates slipping along each other. Disc springs prevent rapid loss of clamping force as wear occurs. Powdered oil shale sprinkled on the rubbing surfaces results in smooth noiseless slipping even after thousands of inches of slipping. Fig. 2 shows a strut, and Fig. 3 shows how wear due to rubbing reduced the slip force of a test strut. As an example of required size of strut, a damper in one bay of the lowest story of a heavy 20-story, 2 sec. period frame, capable of damping 3 bays, might consist of a steel tube 8" x 8" x 1/2", with 3 layers of 1/4" plates on all sides, and clamping bands spaced at 12" centers.

Direction of Future Work

More computer studies will be conducted to include the effects of P-Δ, axial forces, soil-structure interaction, and inelastic frame behavior, and to determine if STFCON and F/W should be varied over the height of the buildings. Additional laboratory work will be conducted to improve the present form of the dampers, to test these as well as extrusion dampers[2] on the Earthquake Simulator, and to develop dampers in other forms such as walls and diaphragms.

References

1. Keightley, W.O., "Prestressed Walls for Damping Earthquake Motions in Buildings," Dept. of Civil Engineering/Engineering Mechanics, Montana State University, Bozeman, Montana, September, 1979.

2. Robinson, W.H. and L.R. Greenbank, "An Extrusion Energy Absorber Suitable for the Protection of Structures During an Earthquake," Earthquake Engineering and Structural Dynamics, V. 4, pp. 251-259, 1976.

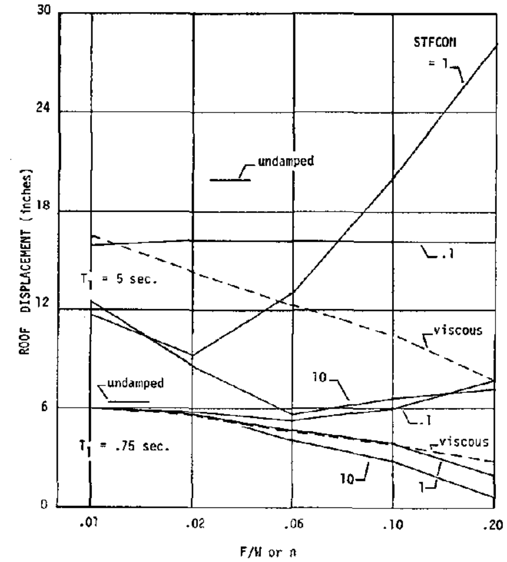


FIG. 1(a) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

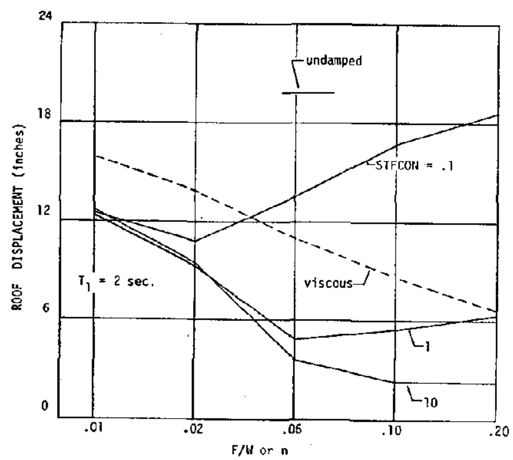


FIG.1(b) - Response Spectra of Friction Damped and Viscous Damped 20-Story Buildings, El Centro 1940 N-S.

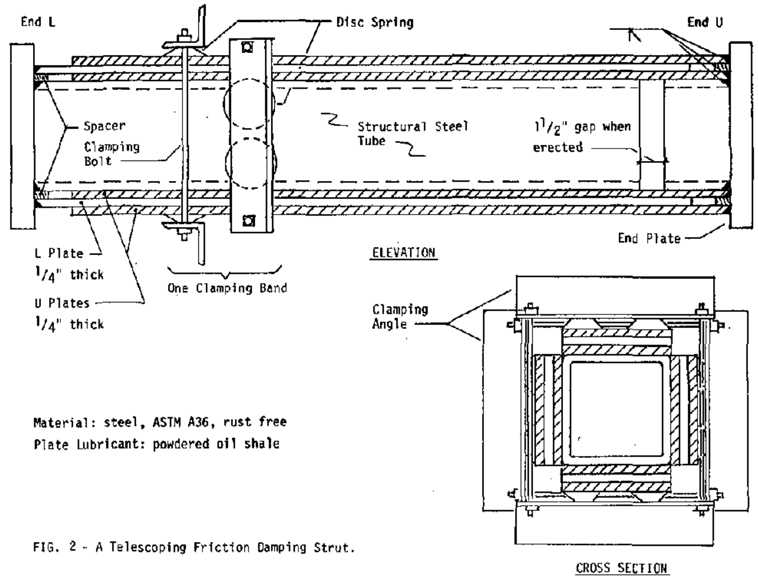


FIG. 2 - A Telescoping Friction Damping Strut.

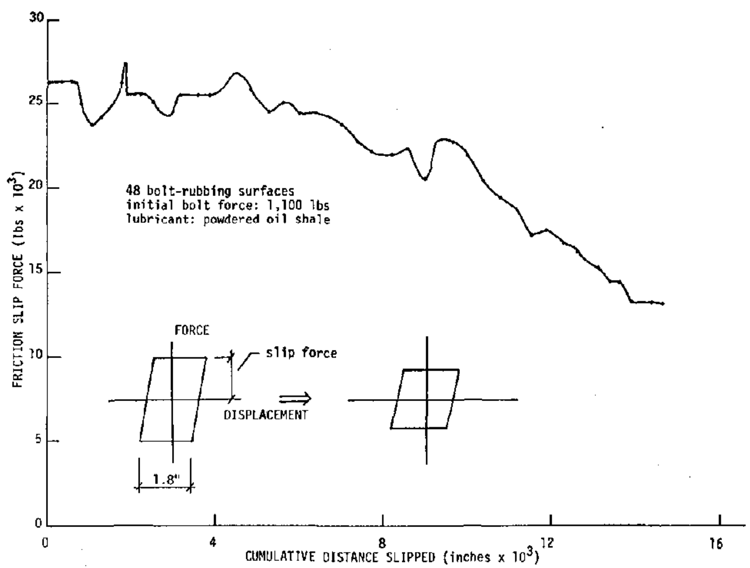


FIG. 3 - Variation of Friction Slip Force With Distance Slipped.

M. SAIIDI

University of Nevada, Reno

An investigation to develop and test analytical models for calculating the nonlinear seismic response of reinforced concrete frame structures is in progress at the University of Nevada, Reno. The study includes both "multi-degree" and "single-degree" analytical models which have been successful in simulating the results from dynamic testing of several ten-story small-scale structures [1]. To evaluate the performance of the analytical models, both small-scale and full-scale structures are being studied.

Response-Analysis of Small-Scale Structures

Four small-scale nine-story three-bay reinforced concrete structures, recently tested at the University of Illinois at Urbana-Champaign, are currently being studied analytically. Each structure comprised two identical frames placed parallel to each other on the test platform. In three of the structures, there was also a central shear wall. The height of the wall was different from one structure to the other, making it possible to study the effect of the height of the wall on earthquake response of structures. The general characteristics of these test models was that the stiffness varied abruptly along the height.

The analytical study of these structures has been focused on a nonlinear single-degree-of-freedom model (called the Q-Model [1]) which has been successful in reproducing the experimental results from structures with no drastic change of stiffness along the height. One of the assumptions made in developing the Q-Model was that the lateral deformed shape of structures remains nearly constant as the nonlinear deformations are developed. For structures with abrupt changes of stiffness, perhaps this assumption is no longer valid, and modifications will be made to obtain a reliable model for structures with or without uniform stiffness.

Response-Analysis of Imperial County Service Building

During the earthquake of October 1979 at El Centro, California, the acceleration response of the Imperial County Services Building was measured at different floors and in the main directions of the building. The building is a six-story reinforced concrete structure with plan-view dimensions of approximately 136 feet by 85 feet, and has five spans in the east-west and three spans in the north-south direction. There are four shear walls in the north-south direction, which extend over the first story. Parallel to these walls, are two exterior shear-walls extend from the second story to the top of the building. Reportedly, the structure developed nonlinear deformations as a result of the earthquake.

The study for this building includes both "multi-degree" and "single-degree" analytical models. The "multi-degree" analysis is aimed at determining: (a) if the assumptions made in structural idealizations are valid, (b) if the hysteretic behavior of the structural connections can be represented well by the available complex hysteresis models, and (c) if the simple hysteresis model (Q-Hyst) introduced in Reference 1 can simulate the measured responses. The computer program used for this part of the study is LARZ [2].

The preliminary results have been promising. Both the complex and simple hysteresis models used in the study have resulted in responses in reasonable agreement with those observed. The waveforms are similar and peak values are close. The results indicate that, for the structure analyzed, it is possible to simulate the overall hysteretic behavior by the Q-Hyst model.

A "multi-degree" analysis is associated with involved data preparation, substantial computer memory space, and considerable computer time. The Q-Model, the nonlinear "single-degree" analytical model introduced in Reference 1, eliminates these difficulties while it results in satisfactory responses for test models. As part of the present study, the Q-Model is being examined to determine its reliability in calculating the response of the Imperial County Services Building, which is a full-scale structure.

Acknowledgements

The data for small-scale test structures have been provided by Dr. Mete A. Sozen, Professor, and Mr. Jack Moehle, research assistant at the University of Illinois at Urbana-Champaign. The measured responses of the Imperial County Services Building were provided by Mr. John Ragsdale and Mr. Randy Rister.

References

1. Saiidi, M. and M.A. Sozen,"Simple and Complex Models for Nonlinear Seismic Analysis of Reinforced Concrete Structures," Civil Engineering Studies, Structural Research Series No. 465, University of Illinois, Urbana, August 1979.

2. Saiidi, M., "User's Manual for the LARZ Family, Computer Programs for Nonlinear Seismic Analysis of Reinforced Concrete Planar Structures," Civil Engineering Studies, Structural Research Series No. 466, University of Illinois, Urbana, November 1979.

3. Saiidi, M. and M.A. Sozen, "A Naive Model for Nonlinear Response of Reinforced Concrete Buildings," accepted for publication in the Proceedings of the Seventh World Conference in Earthquake Engineering, Istanbul, Turkey, September 1980.

4. Saiidi, M., "Influence of Hysteresis Models on Calculated Seismic Response of Reinforced Concrete Structures," accepted for publication in Proceedings of the Seventh World Conference in Earthquake Engineering, Istanbul, Turkey, September 1980.

5. Saiidi, M., "A Simple Model for Nonlinear Seismic Analysis of Reinforced Concrete Structures," accepted for presentation at the International Conference on Recent Advances in Structural Dynamics, Southampton, England, July 1980.

C. C. CHEN
University of Notre Dame

TEOMAN ARIMAN
The University of Tulsa (Visiting)

L.H.N. LEE
University of Notre Dame

Extended Summary

Buckling failure of long buried pipelines during an earthquake has been recognized as an important problem in the lifeline earthquake engineering. This important and unfortunately long neglected area has recently attracted a great deal of attention of earthquake engineers and researchers both in theoretical and experimental studies (1,2). However, investigations on the critical buckling load of buried pipelines due to axial compressive loading have been scarcely found although the stability equations for cylindrical shells have been available in the literature since the late 1800's. The studies on this subject are, however, usually simplified and restricted to a common beam on an elastic foundation (2).

The purpose of this work is to investigate the buckling failure mode of buried pipelines of a cylindrical shell surrounded by uniform springs (3). Donnell's cylindrical shell equations are used for quasi shallow shells and Flügge shell equations are employed when the shallow shell equations are not applicable. As the first step in this quite complicated area and with a conservative approach the buried pipe is quasi-statically investigated under seismic loads and the critical acceleration is estimated when the static buckling load is related to the inertia force of the system. Attention is then focused on a parametric study that concerns the effects of the dimensions of the pipe as well as the stiffness of the soil medium surrounding the pipe.

Results of this work have first shown that there is no significant half sine wave occurring in the circumferential direction for relatively long pipes (Donnell's shell equations) when the axial compressive load reaches its minimum. This fact is intuitively expected for cases in which the surrounding soil medium has large stiffness. It is therefore reasonable to assume that the pipe deforms in such a manner that its deformed shape is totally governed by the number of sine waves in the axial direction. Figures (1) and (2) show for the half sine waves $\hat{m}$, the variation of the critical axial load P with respect to the Batdorf parameter (4) $Z = L^2/ah(1 - \mu^2)^{1/2}$ for a thin walled pipe. Here L is the length and μ is the Poisson's ratio of the shell; h and a represent the wall thickness and mean radius respectively. The shell is surrounded by a uniform soil medium with extensional stiffness k, in the radial direction. It is interesting to note that for a given pipe, an increase in soil stiffness causes a decrease in wavelength of the unstable mode. An increase in the crucial critical load is however, noted.

Some representative results for the Flügge's shell equations case are represented in Figures (3) and (4). The parameter which is related to the axial compressive load P is plotted versus $L/\hat{m}a$ for a ductile iron pipe with L = 40 ft, a = 24 in., h = 0.51 in. for two extreme values of soil nondimensional parameter α ($\alpha = \frac{k}{(Eh/a^2)}$ and E is the Young's modulus for ductile-iron). $\alpha = 0$ represents the case of no soil medium around the pipe. Results show that as long as all points lie below the area covered by the curves, the pipe is stable. As soon as a point reaches one of the curves, the pipe is in neutral equilibrium and at the onset of buckling. Results show that the soil medium around the pipe has quite substantial effect on the critical axial load.

REFERENCES

1. Teoman Ariman, "A Review of the Earthquake Response and Aseismic Design of Underground Piping Systems." The Current State of Knowledge of Lifeline Earthquake Engineering, 282-292, ASCE, New York, 1977.

2. Teoman Ariman and Gregory E. Muleski, "Seismic Response of Buried Pipelines -- A Review." Lifeline Earthquake Engineering -- Buried Pipelines, Seismic Risk and Instrumentation, edited by T. Ariman, S. C. Liu, and R. E. Nickell, 1-30, ASME PVP-34, New York, 1979.

3. Gregory E. Muleski, Teoman Ariman, and Carl P. Aumen, "A Shell Model of a Buried Pipe in a Seismic Environment." Journal of Pressure Vessel and Technology, Vol. 101, 39-44, 1979.

4. D. O. Brush, and B. O. Almroth, Buckling of Bars, Plates and Shells, McGraw-Hill, 1975.

ACKNOWLEDGMENT

This work is supported by National Science Foundation under the Grant No. ENV-77-23236 in which Dr. S.C. Liu is the Program Director.

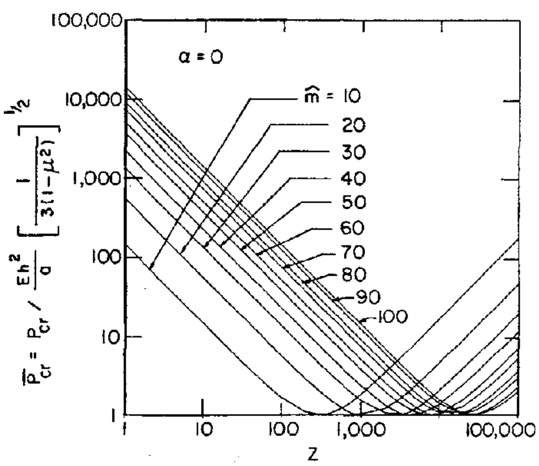


FIGURE 1

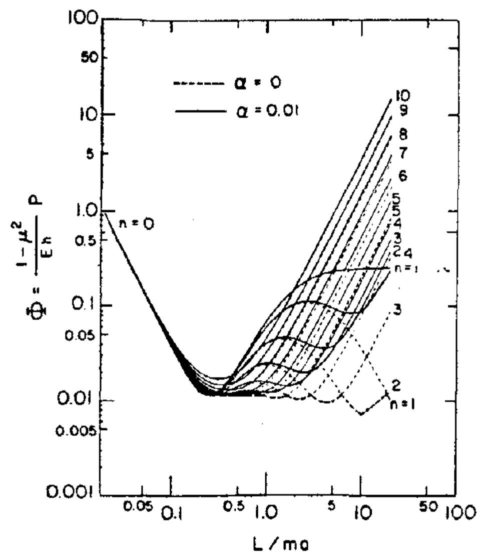


FIGURE 3

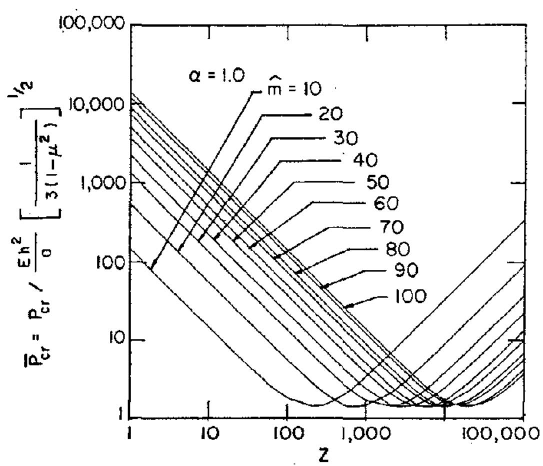


FIGURE 2

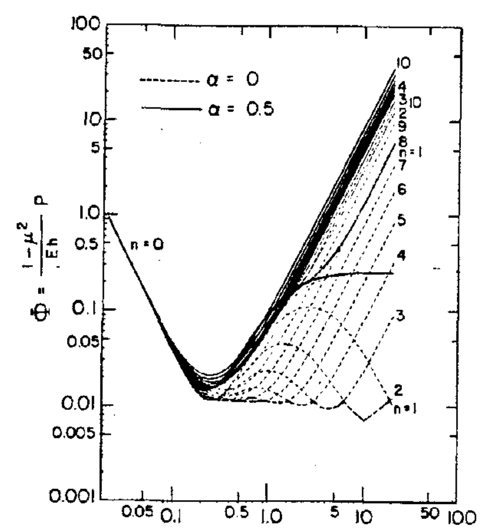


FIGURE 4

AHMED M. ABDEL-GHAFFAR

Princeton University

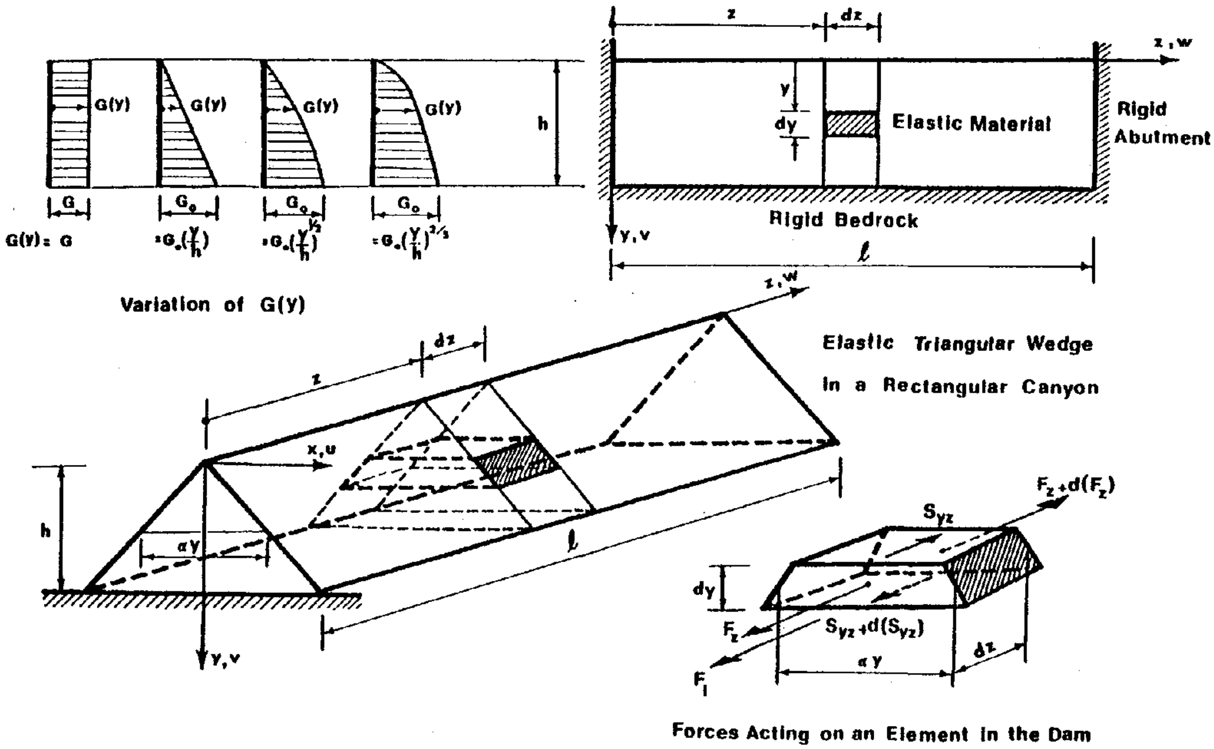
This brief synopsis describes a research project, which is in progress, on the longitudinal vibration behavior of earth dams during earthquakes. The problem is of practical interest in that such longitudinal vibrations may lead to cracks, which may later enlarge and produce catastrophic conditions under further earthquake impulses and other stresses. Financial support for this research is provided by the National Science Foundation (Research Initiation in Earthquake Engineering Hazards Mitigation). The two principal objectives of the investigation are apparent in the following two research phases.

Development of Analytical Models

Analytical models are developed for evaluating dynamic characteristics, namely natural frequencies and modes of vibration, and for estimating earthquake induced strains and stresses (both shear and normal or axial) on earth dams in a direction parallel to the dam axis. In these models the nonhomogeneity of the dam's materials were taken into account by assuming a certain variation of stiffness properties along the depth of the dam (Fig. 1). Cases such as constant elastic moduli, linear variation of elastic moduli, and elastic moduli increasing as the one-half, one-third, two-fifths and a general (ℓ/m)th powers of the depth are studied. In addition, results of full-scale dynamic tests, of both ambient and forced vibrations (already conducted by the principal investigator), and real earthquake observations of some existing dams are utilized to confirm and improve the suggested models. It was found that the models which take into account the effect of variation with depth of both the shear modulus and the modulus of elasticity of the dam material are the most appropriate representations for predicting the dynamic characteristics in the longitudinal direction. The agreement between the experimental and earthquake data and the theoretical results is reasonably good.

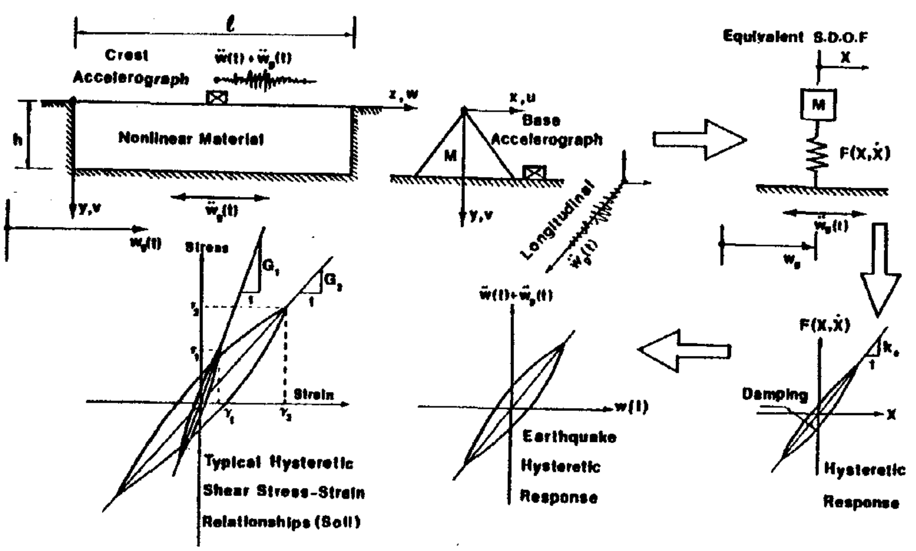
Identification of Elastic Moduli and Damping Factors of Earth Dams from Earthquake Records

Based on the above-mentioned, longitudinal analytical models, a rational procedure is being developed to estimate dynamic strains and corresponding elastic moduli and damping factors for earth dams from their hysteretic responses to real earthquakes, utilizing the hysteresis loops from the crest as well as the base records of earth dams (Fig. 2). This leads to a study of the nonlinear behavior in terms of the variation of stiffness and damping properties with the strain levels of different loops. Finally, the data so obtained will be compared with those previously available from soil-dynamics laboratory investigations; the data also will be combined with those obtained from the analysis of the upstream-downstream vibrations (conducted by the principal investigator) to give informative materials to both the earthquake and the geotechnical engineers. Figure 3 shows some of the hysteresis loops (of the first mode of longitudinal vibration) of Santa Felicia Earth Dam (in Southern California) which resulted from the dam's response (in the longitudinal direction) to the San Fernando earthquake (M_L = 6.3) of 1971.



THE TWO DIMENSIONAL ELASTIC MODEL (Shear & Axial Deformations)

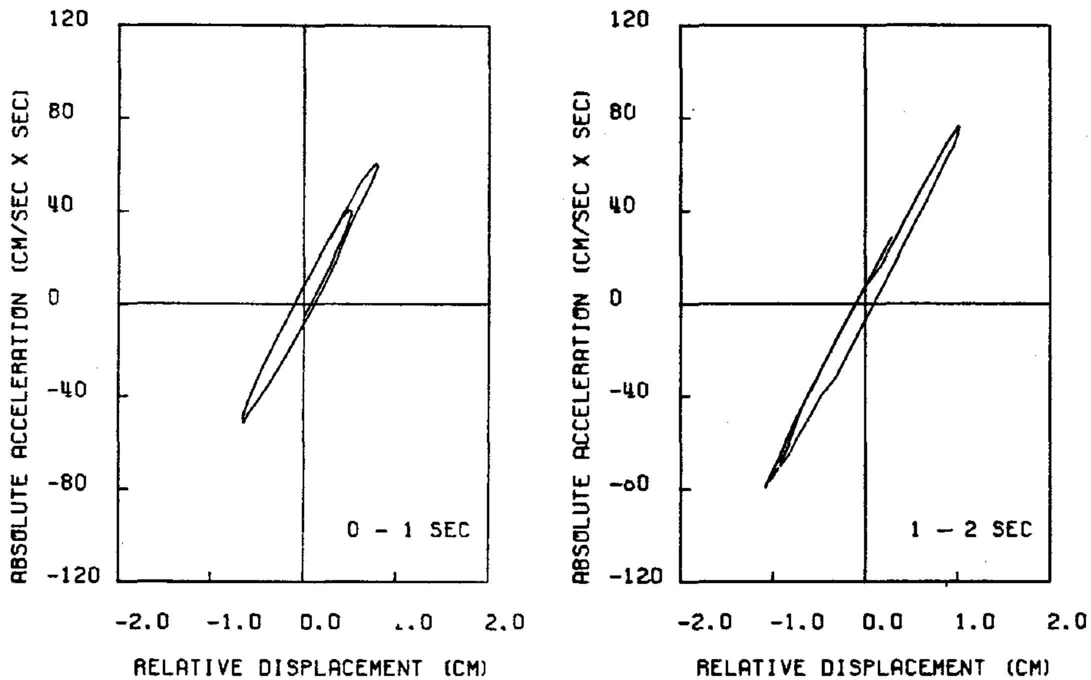
Figure 1



IDENTIFICATION OF ELASTIC MODULI AND DAMPING FACTORS FROM EARTHQUAKE RECORDS

Figure 2

SANTA FELICIA DAM, CALIFORNIA,
COMPONENT ROTATED TO LONGITUDINAL DIRECTION
HYSTERETIC RESPONSE FILTERING TYPE C



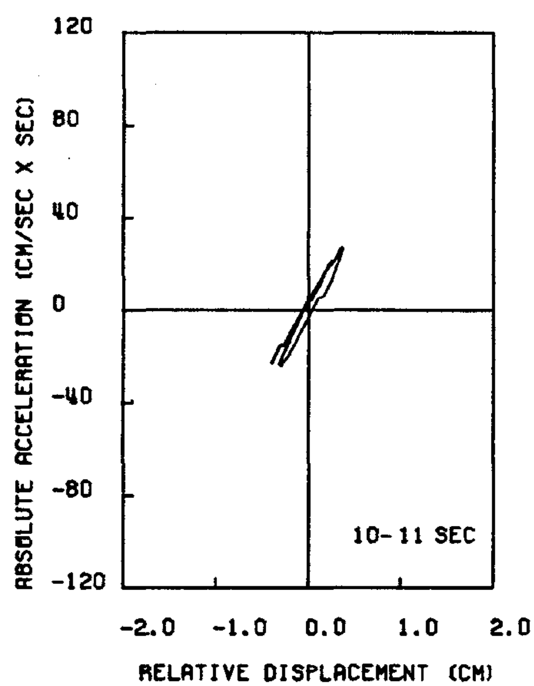


Figure 3

AHMED M. ABDEL-GHAFFAR AND ROBERT H. SCANLAN

Princeton University

A comprehensive study dealing with the earthquake-response analysis of long- and intermediate-span bridges when subjected to multiple-support seismic excitations is part of the current earthquake engineering research in the Civil Engineering Department at Princeton University; it is in the proposal stage and has been submitted to the National Science Foundation (Division of Problem Focused Research Applications).

The research is concerned, in general, with: (1) the definition of the expected seismic inputs, (2) the earthquake-response analysis, and (3) general seismic design criteria of long-span suspension bridges, and incidentally of intermediate-span cable-stayed bridges, when subjected to multiple-support seismic excitations (Fig. 1). Efforts will be made to assess the main parameters controlling the three-dimensional dynamic performance of these bridges under traveling seismic waves. In addition, recommendations for economical and appropriate deployment of strong motion instrumentation will be made. An outline of the research plan is summarized below.

Structural and Dynamic Analysis

The research requires, as a prerequisite, extension of the studies which were started by one of the principal investigators in order to establish more accurate dynamic characteristics of both suspension and cable-stayed bridges. In particular, this first phase of the investigation concerns the development and refinement, both analytically and numerically, of the dynamic-analysis methodology for long-span bridges, taking into account among other things the structural (coupled) vibration problem, large vibrational displacements, and the effect of the suspended structure's geometry which may or may not be conventional.

Definition of Appropriate Seismic Inputs

The second phase of the investigation deals with the appropriate definition of seismic inputs (to permit estimation of relative motions between support points, as shown for a simplified case in Fig. 2), taking into account the propagation, attenuation and phase characteristics of seismic waves as evident from existing and newly acquired strong-motion records. The seismic inputs will be time functions (such as cross-correlation functions) and for frequency functions (such as cross-spectral functions). The form of these time and frequency functions will be determined with the aid of available strong motion accelerograph records (at one location and at another nearby within the range of a bridge span), random vibration theory and elastic wave propagation theory, as shown in Fig. 3.

Earthquake Response Analysis

Earthquake response characteristics of selected bridges, representing a wide band of long-span bridges, will be determined in the third phase of the study. In addition, comprehensive studies of the bridge components and integrated analytical and numerical procedures will be developed on the three-dimensional linear (elastic) and nonlinear (geometric) behavior of these structures under simultaneous seismic loading conditions (Fig. 4 shows a simple example of using the suggested seismic inputs of Fig. 3 in statistically studying the earthquake response of a suspension bridge).

Earthquake Resistance Criteria and Recommendation for Strong-Motion Instrumentation

Finally, earthquake resistance criteria for design, strengthening and repair will be suggested, and recommendations for purposeful and economical deployment of strong ground motion instruments, on and in the vicinity of these important structures, will be made.

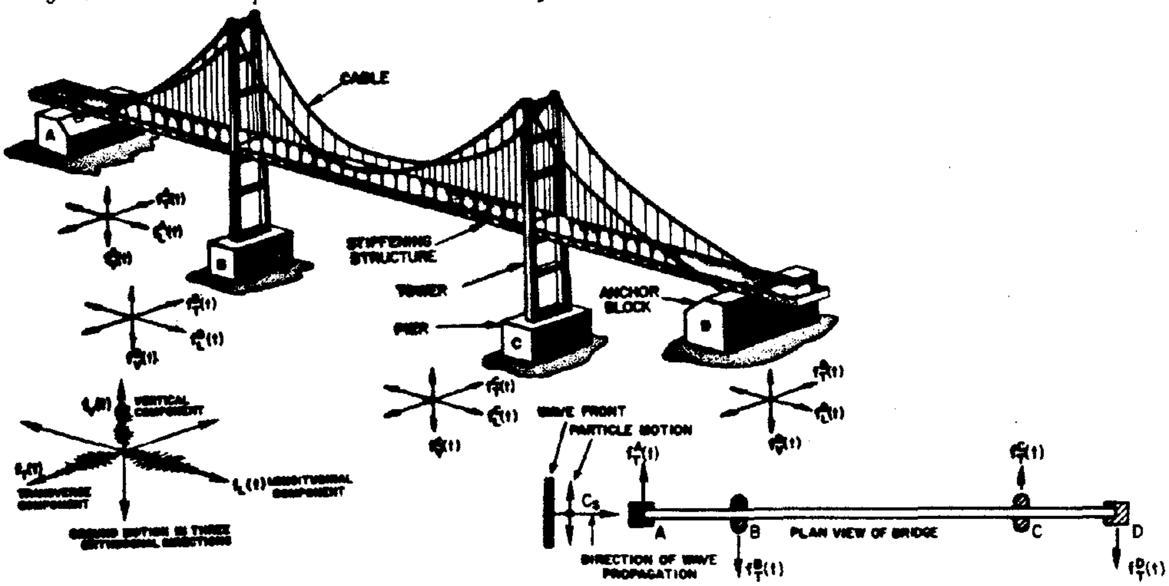


Figure 1

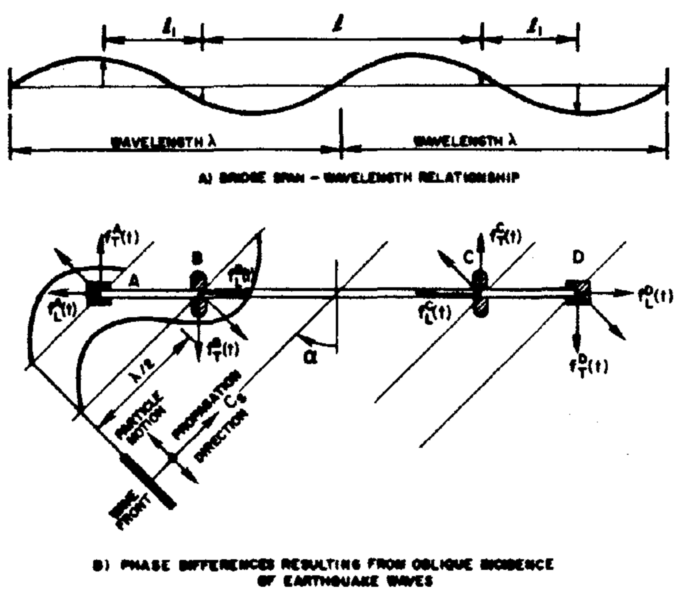
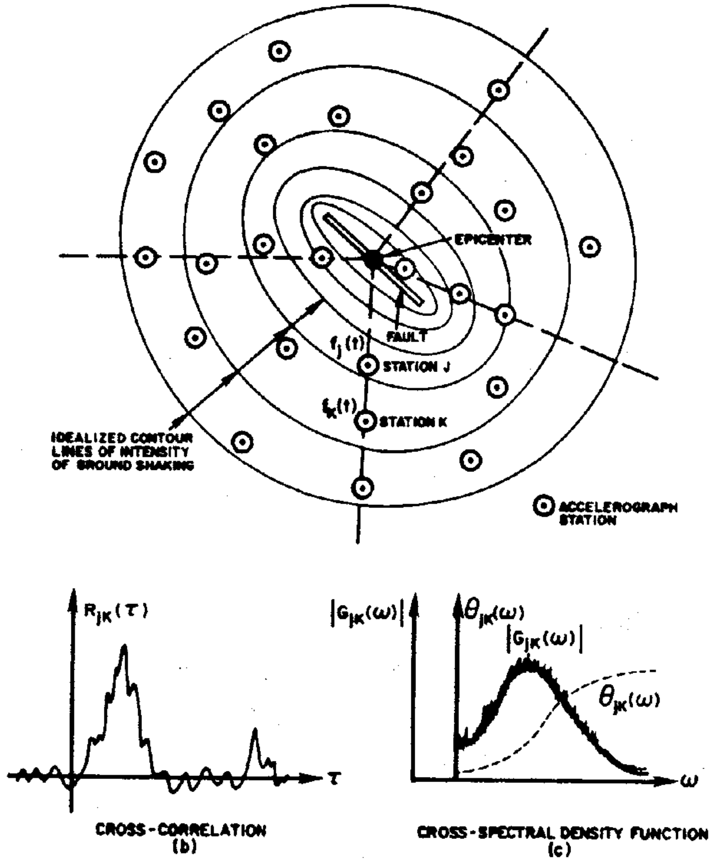


Figure 2

Figure 3



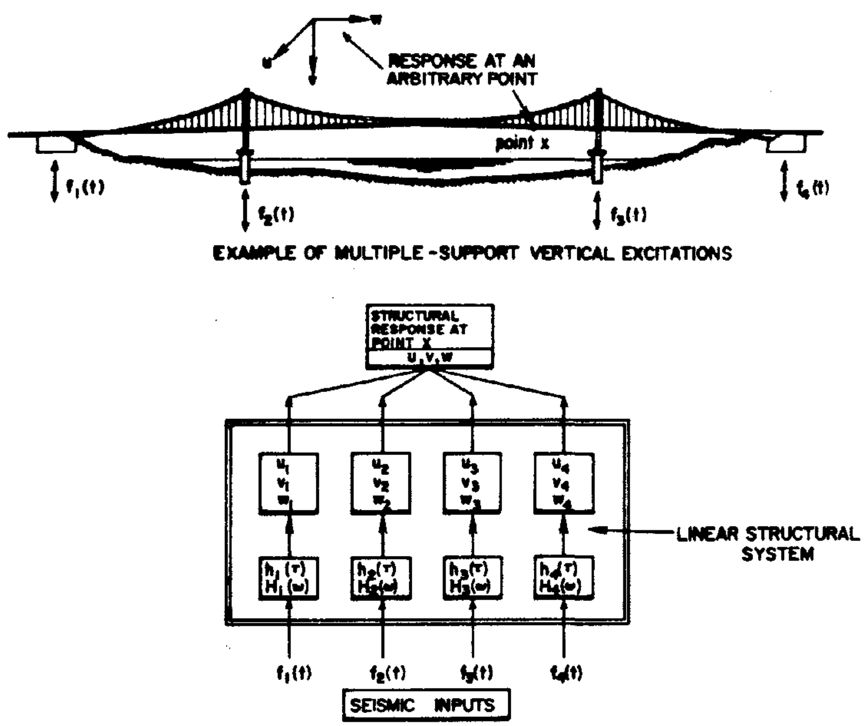


Figure 4

T.Y. YANG and J.L. BOGDANOFF

Purdue University

Free vibrations and seismic responses of the major structural components in two large fossil fuel steam generating power plants have been studied under the support of National Science Foundation. Some analytical results for some structural components are presented.

Column-Supported Cooling Tower

Half of the shell is modeled using orthotropic quadrilateral flat plate finite elements. The supporting columns and top ring beam are modeled by beam finite elements.

The time-history response of 30 seconds to the North-South accelleration component of the May 18, 1940 El Centro earthquake is computed by the technique of modal superposition. A response spectrum analysis is used to ascertain the maximum response of the first three eccentric modes with 4% critical damping. From a RMS estimate of the total maximum response, forces and stresses in the shell and columns are obtained. The contribution of gravity loading is included.

Only those modes with one circumferential wave are excitable by horizontal earthquake motion. In this study, the contributions of the higher eccentric modes to the total deflection rapidly diminish. In the undamped case, the first mode contributes approximately 90% of the total deflection while the second and third modes contribute 9% and 1%, respectively. When damping of 4% of the critical value is included, the first mode accounts for over 96% of the total response, with the second mode adding approximately 4%, and the third mode's contribution is negligible.

Consideration must be given to the effect of the discrete supporting columns in order to accurately analyze the seismic response of cooling towers. The columns are found to be the vulnerable region in the system. In particular, the axial force in the columns appears to be the most critical.

The response of the cooling tower shell is characterized by predominantly membrane behavior. Bending is restricted to a narrow band at the base of the shell.

A 9x10 element mesh with 918 degrees of freedom is practically adequate for the purpose of predicting the dynamic behavior of the cooling tower. For more detailed stress predictions, however, a finer mesh size, using quadrilateral plate elements exclusively, or more sophisticated shell finite elements would be needed. Also, inelastic deformations, which may affect the dynamic behavior, have not been considered.

Doubly Curved Membrane Shell Finite Element for Cooling Towers

A high-order, doubly-curved, quadrilateral membrane shell finite element has been developed with the intent of application to the study of the response of column-supported cooling towers. The element is defined by lines of principal curvature and allows a third-order mapping of the meridian. The inplane displacement assumptions are bicubic. The transverse displacement assumption is bilinear. Three rigid body modes, two inplane translations and a rotation about the shell normal are implicitly included. They are sufficient to produce excellent convergence characteristics in analyzing membrane shells, regardless of the shell's Gaussian curvature. Numerical studies, both static and dynamic, demonstrate the excellent efficiency of the present element.

It remains to incorporate the present membrane element in a structural analysis program which includes a sophisticated general bending shell element and beam elements. Once this has been accomplished, it is believed that accurate and reliable solutions can be obtained for the cooling tower problem with a substantially less computational effort than that required in using a fine-mesh, flat plate model.

Reinforced Concrete Chimney

An analytic investigation of the elastic and inelastic response behaviors of an 823 feet chimney to the El Centro earthquake record has been conducted. The chimney is modelled by using eight pipe-type beam finite elements. Equations of motion are solved numerically by direct integration method. For the pure elastic analysis, cracks developed in the chimney are considered. Several assumed percentages of the critical damping are also considered. For the inelastic analysis, the material of the chimney is assumed to be an idealized equivalent homogeneous material with the same Young's modulus, mass density, and elastic limit as concrete. Equations for the determination of the depths of elastic-plastic boundaries in the finite elements are derived. The time-history response results obtained from the inelastic analysis are compared with those obtained from the purely elastic analysis. The present results may be of practical value to the structural designers for chimneys. The present method may be applied to the analysis of practical designs of slender reinforced concrete chimneys.

Coal Handling Elevator Supporting Structure

The supporting structure for coal handling elevator in the 1200 MW steam generating plant at Paradise, Kentucky is studied. An adequate model for analyzing the dynamic behavior of the system, required the use of over 1000 three-dimensional truss, beam, and plate finite elements and approximately 100 lumped masses. The assembled system has 714 degrees of freedom. The analysis has accomplished the following objectives:

a) Determine the basic dynamic properties of the system, i.e., the natural frequencies and their corresponding normal modes. b) Perform a response spectrum analysis to determine the necessary number of modes to be included in an earthquake time-history response analysis and to provide a means of checking the time-history calculations. c) Determine the response of the coal handling equipment to the North-South component of the El Centro, 1940, earthquake using the mode superposition technique and investigate the effect of viscous damping of the response. d) Identify the vulnerable members of the structure. e) Utilize 3-D computer graphics techniques for data checking, displaying results, and as a medium for gaining insight into the nature of the structure's dynamic behavior.

Steam Generator and Supporting Structures

Seismic analysis has been performed for a 600 MW and a 1200 MW steam generators and their supporting structures in this study using realistic three-dimensional finite element models. The 600 MW power plant is located in Zone III of the earthquake risk map whereas the 1200 MW power plant is located in Zone I. Because of greater possibility of an occurance of an earthquake in Zone III, the power plant was designed according to the specifications of the Unifrom Building Codes. Each suspended boiler is analyzed by an analytic model as well as by a finite element model with four hanger rods.

For each plant, twelve natural frequencies and associated mode shapes of the combined boiler and structure finite element model have been obtained. For both boiler-structural systems, the spectra of modal responses of the relative displacements of the joints and the axial stresses in the structural members are obtained based on El Centro earthquake of May 18, 1940. The statistical maxima of member axial stresses are based on the root-mean-square values.

It is found that for the 600 MW boiler-structure, the axial stresses in 158 out of 1607 members exceed the yield stress, most of which are located in the rear lower portion of the supporting structure. The axial stresses in 309 members exceed the Euler buckling values. These are mostly cross-bracing members. Only in 4 out of 20 tie members the axial stresses exceed the yield value. The axial stresses in the same 4 tie members exceed their corresponding Euler buckling values. Small damping coefficients reduce the response displacements significantly.

It is found for the 1200 MW boiler-structure that out of 1290 members, the maximum principal direct stresses exceed the elastic limit in 277 members, the ultimate stress in 85 members. The maximum shearing stress exceed the elastic limit in 142 members. The axial forces exceed the Euler buckling values in 319 members. The higher stresses are generally found in the lower parts of the major columns and the columns in the front portion of the structure that are tied to the air heater. The horizontal tie members are the most vulnerable components of the structure. The axial stresses in 9 out of 11 tie members exceed the elastic limit as well as the Euler buckling loads.

JAMES T. P. YAO and KING-SUN FU

Purdue University

To-date, relatively few experienced engineers are qualified to assess seismic damage of existing structures. In recent years, several governmental agencies have made attempts to simplify this process to enable more engineers and technicians to perform this important work. Nevertheless, structural damage is a very complex pheonomenon, which is difficult to understand and analyze in a clear and precise manner.

In current practice, the damage of a given structure can be studied both experimentally and analytically in case of need. Experimental studies include either field surveys or laboratory tests; and field surveys include the detection of failed components and other evidence of distress, the application of non-destructive testing techniques to the structure, the discovery of poor workmanship and construction details, and proof-load and other load testing of a portion of a very large structure. Meanwhile, samples can be collected from the field and tested in the laboratory to obtain strength and other mechanical properties. Analytical studies frequently consist of the examination of the design calculations and drawings, the review of project specifications, the performance of additional structural analyses incorporating field observations and test data, and the possible explanation and description of the event under consideration. Although such general procedures exist, the detailed methodology, especially the decision making process, remain as priviledged information for a relatively few and are being transmitted to younger engineers primarily thorugh many years of working experience and the development of "intuition".

The objective of this research project is to develope a direct and systematical methodology for the assessment of seismic damage of existing structures. The subject matter was discussed in several state-of-the-art papers [1-6]. The possible application of the theory of pattern recognition was considered [7]. In addition, an exploratory study of the theory of fuzzy sets was made for possible applications [8]. Results of these investigations were summarized in a technical report [9]. In the present research project (NSF Grant No. PFR 7906296), the following tasks are being pursued:

(1) <u>Formulation of the Problem of Damage Assessment</u>:

The problem of damage assessment will be examined in the context of pattern recognition [10-12], which deals with the description, classification and interpretation of data. It is desirable to obtain a mathematical formulation with emphases on (a) the formulation of a decision function or classifier, (b) the development of a procedure for the feature extractor, and (c) the understanding of the underlying data structures. The usefulness of currently available field data for damage assessment should be studied. Moreover, the need for additional information not currently available will be considered.

(2) Identification of Significant Parameters:

With the mathematical formulation of the problem, attempts will be made to identify significant parameters, which are measurable or can be computed from currently available data. In addition, it is desirable to find additional parameters of importance which are not being collected and analyzed at present. It is expected that these parameters can be ranked according to their respective significance in relation to the overall damage state.

(3) Illustration and Demonstration:

Special cases of experimental results and field data will be analyzed for the purpose of illustration and demonstration of such a methodology. Preliminary results will be used to refine the mathematical model and its associated computational algorithms. In so doing the practicality and feasibility of this methodology can also be examined.

(4) Collection, Processing, and Interpretation of Existing and Available Test Data and Records:

Field records and laboratory test data will be collected. Whenever it is possible, the methodology thus developed will be applied. Additional tests will be proposed if such information and data are not readily available for the implementation of this methodology. Because of the practical nature of the ultimate goal of this research topic, close contact will be maintained among academic researchers and practicing engineers.

This study is coordinated and managed by Principal Investigator, J. T. P. Yao, who is working closely with the Co-Principal Investigator, K. S. Fu, whose research interests are in the areas of pattern recognition and fuzzy sets. They are assisted by a post-doctoral research associate specializing in patter recognition, Dr. Mitsuru Ishizuka; and two graduate students one each in electrical and civil engineering, Messrs, Hsi-Ho Liu and Sassan Toussi, respectively.

References

[1] Rodeman, R., and Yao, J. T. P., "Structural Identification - Literature Review", Technical Report No. CE-STR-73-3, School of Civil Engineering, Purdue University, December 1973, 36 pages.

[2] Hart, G. C., and Yao, J. T. P., "System Identification in Structural Dynamics", Journal of the Engineering Mechanics Division, ASCE, v. 103, n. EM6, December 1977, pp. 1089-1104.

[3] Chen, S. J. Hong, Methods of System Identification in Structural Engineering, MS. Thesis, School of Civil Engineering, Purdue University, West Lafayette, IN 47907, August 1976.

[4] Ting, E. C., Chen, S. J. Hong, and Yao, J. T. P., System Identification, Damage Assessment and Reliability Evaluation of Structures, Purdue University, February 1978, 62 pages.

[5] Liu, S. C., and Yao, J. T. P., "Structural Identification Concept", Journal of the Structural Division, ASCE, v. 104, n. ST12, December 1978, pp. 1845-1858.

[6] Yao, J. T. P., "Damage Assessment and Reliability Evaluation of Existing Structures", Engineering Structures, V. 1, October 1979, pp. 245-251.

[7] Fu, K. S., and Yao, J. T. P., "Pattern Recognition and Damage Assessment", Proceedings, Third ASCE EMD Specialty Conference, University of Texas, Austin, TX, 17-19 September 1979, pp. 344-347.

[8] Yao, J. T. P., "An Approach to Damage Assessment of Existing Structures", Technical Report No. CE-STR-79-4, School of Civil Engineering, Purdue University, West Lafayette, IN, October 1979, 25 pages.

[9] Yao, J. T. P., "Reliability of Existing Buildings in Earthquake Zones - Final Report", Technical Report No. CE-STR-79-6, School of Civil Engineering, Purdue University, West Lafayette, IN, December 1979, 50 pages.

[10] Andrews, H. C., Introduction to Mathematical Techniques in Pattern Recognition, Wiley-Interscience, 1972.

[11] Mendel, J. M. and Fu, K. S., Editors, Adaptive, Learning and Pattern Recognition Systems, Academic Press, 1970.

[12] Fu, K. S., Syntactic Methods in Pattern Recognition, Academic Press, 1974.

L. D. LUTES

Rice University

This summary describes some results of current research at Rice University on the problem of predicting first-passage probabilities for simple linear structures subjected to stationary stochastic excitation. This work is part of amore general study of the Response of Structures to Stochastic Excitations sponsored by the National Science Foundation.

Problem Formulation

Let L(b,t) represent the probability that the absolute value of a stochastic process X has never reached the level b prior to time t. Thus L is the probability that first-passage has not yet occurred, or is the probability of survival if b represents a failure condition. One can define a function $\alpha(t)$ such that

$$L = \exp(-\int_0^t \alpha(\tau)\, d\tau) \tag{1}$$

and it has been shown that $\alpha(t)$ then represents the conditional rate of upcrossing of the level b at time t, given that no upcrossings have occurred prior to time t. When X is, or tends to, a stationary process then $\alpha(t)$ tends to a stationary value α_0 and for large t values eq. (1) can be rewritten as

$$L = L_0 \exp(-\alpha_0 t) \tag{2}$$

For obvious reasons α_0 is often called the limiting decay rate of survival probability. An often used approximation for α_0 is the unconditional rate of upcrossings of the level b when X is stationary, which will be denoted by ν_0. This study focuses on the values of α_0/ν_0 and L_0 (for large time) and on the time dependence of $\alpha(t)$ for small time values.

SDF Linear Structure

An empirical formula for α_0/ν_0 has been obtained as

$$\alpha_0/\nu_0 = 1-1.075\ [k \exp(-k/2]^w \tag{3}$$

where

$$k = b/\sigma_0 \tag{4}$$

with σ_0 = stationary value of the rms of X, and w is a function only of the amount of damping in the structure. In particular, w is taken as a linear function of Vanmarcke's [1] bandwidth parameter q^2, which for small values of ξ (fraction of critical damping) can be approximated by

$$q^2 \doteq (4/\pi)\, \xi(1-1.1\xi) \tag{5}$$

and

$$w = 0.2364 + 28.14q^2 \tag{6}$$

The results of these equations have been shown to agree quite well with empirical data from numerical simulation of the problem for ξ values down to 0.01 and for k values in the range of 1 to 3.5, and also to agree with the results of extensive numerical computation by Roberts [2] using a Kolmogorov equation to compute the diffusion of probability for an approximation of the original problem.

It has also been found empirically that the L_0 term seems to be independent of ξ and can be approximated by

$$L_0 = \exp\,[\exp(-1.195 - 0.3106\,k^2)] \tag{7}$$

It has been found that a useful approximation to the nonstationary buildup of $\alpha(t)$ is given by

$$\alpha(t) = \frac{2/T}{1 - \exp(-rt)} \exp\left[\frac{-a}{1 - \exp(-rt)}\right] \tag{8}$$

where

$$a = -\log\left(\frac{\alpha_0}{\nu_0}\right) - \frac{k^2}{2} \tag{9}$$

and

$$r = \frac{\alpha_0}{\log(L_0)} [\gamma + \log(a)] \tag{10}$$

where $\gamma = 0.577216$ is Euler's constant, and T is the period of the oscillator. Rather than perform the integration of α given in eq. 1, one can obtain an approximation of L at the discrete times $t_n = nT/2$ by using

$$L(b,t_n) = L(b,t_{n-1})\exp\{-\frac{T}{2}\,\alpha[(n - \frac{1}{2})\,\frac{T}{2}]\} \tag{11}$$

with the initial condition $L(b,0) = 1$. Note that this recursive computation need only be performed for a relatively few half-cycles since eq. 11 tends to eq. 3 (to a close approximation) as $\alpha(t)$ tends to its stationary value.

2DF Linear Structures

It has been found that the α_0/ν_0 values for a two-degree-of-freedom structure cannot, in general, be determined from those for SDF systems by use of only a bandwidth parameter. For example, in some situations the α_0/ν_0 value for a 2DF system may be lower than that for a SDF system with the same modal damping, whereas the bandwidth parameter is always increased by addition of a second mode, so predicts increased values of α_0/ν_0. Studies are continuing on the dependence of α_0/ν_0 and L_0 on the modal frequencies and the relative response contributions of the two modes.

---

1. Vanmarcke, E. H., "Properties of Spectral Moments with Applications to Random Vibration," Journal of the Engineering Mechanics Division ASCE, Apr. 1972, pp. 425-446.

2. Roberts, J. B., "First Passage Probability for the Envelope of a Randomly Excited Linear Oscillator," Journal of Sound and Vibrations, Vol. 46, No. 1, 1976, pp. 1-14.

RICHARD K. MILLER

University of Southern California

Presented herein is a summary of research supported by the National Science Foundation in the area of approximate analysis of the nonlinear response of structures to dynamic loads. Attention is focused on three specific problems: the dynamics of structures with localized nonlinearity, the propagation of elastic waves in frictionally bonded solids, and the development of equivalent linearization techniques for the finite element analysis of nonlinear frame vibrations.

The Dynamics of Structures with Localized Nonlinearity

As many investigators have noted, nonlinear structural behavior often occurs at a single identifiable location within a structure. The analysis of the dynamic response of such systems is greatly simplified by taking advantage of this natural division of the system into a linear subsystem(s) and a single nonlinear structural element. Research in this area, which began two years ago, has focused on the response of adjacent multidegree-of-freedom linear systems which are interconnected by one nonlinear structural element, and subjected to base excitation. While most investigators concerned with locally nonlinear systems have concentrated on the development of substructuring techniques for large finite element computer codes, the approach used in our research has differed by concentrating on the development of approximate *analytical* techniques for simplified structural models. The goals of this research are to develop efficient analysis techniques capable of reducing computational costs and identifying important parameters for use in design. Significant progress has been made toward the accomplishment of these goals for systems with small or moderate levels of nonlinearity and subjected to steady harmonic or stationary stochastic excitation. Numerical examples considered include adjacent single story frames separated by a seismic joint, or interconnected by a rigid-plastic structural element. A Ph.D. thesis summarizing these results is currently in preparation. Goals for future research include an investigation of the inclusion of weighting functions in the linearization integrals for the purpose of improving the accuracy of the approximate solutions for systems with large nonlinearity.

The Propagation of Elastic Waves in Frictionally Bonded Solids

An understanding of the effects of friction and slippage at an interface between elastic solids is fundamental to the mechanics of strike-slip faulting, attenuation in the near field, and energy dissipation at slipping interfaces within structural systems. The goal of this research, which began three years ago, is to develop an approximate solution technique capable of simplifying the analysis procedures to the extent that realistic nonlinear models for the bonding friction may be included, even in preliminary studies. To accomplish this goal, an equation averaging technique has been developed and applied to the problem of reflection, refraction and absorption of steady harmonic SH, SV and P waves, and to the attenuation and dispersion of Love-type surface waves in a frictionally bonded layer. Goals for future research include an investigation of the effects of friction and slippage at an interface on the propagation of elastic waves with *stochastic* time dependence. Studies of such nonlinear probabilistic wave propagation may form a useful framework for future earthquake studies. Other future research is aimed at investigating interface waves of Stonely-type, and surface waves in multilayered solids with frictionally bonded surfaces.

Equivalent Linearization Techniques for Finite Element Analysis of Nonlinear Frame Vibrations

The analysis of nonlinear vibration of large structural frames is most often accomplished by existing nonlinear finite element codes. While such codes are capable of providing much useful detail, the excessive computational costs involved often prevent their use in design studies. On the other hand, design studies may often require less detail and accuracy than that provided by a typical nonlinear finite element code. The goal of this research, which is in a very preliminary stage, is to develop a simplified analysis procedure whereby the governing nonlinear equations of motion may be appropriately linearized by an extension of the method of equivalent linearization, in order to facilitate a semi-analytical solution and thereby reduce computational costs. The aim is to develop a procedure at the element level which will require relatively minor modification of existing codes for implementation. This project is not yet funded, and is a joint effort with Professor L.C. Wellford, Jr. Initial consideration is being given to the effects of geometrical nonlinearities on the response of beam-column systems.

P-T.D. SPANOS

University of Texas at Austin

Research is being conducted in the area of analytical methods for probabilistic analyses of seismic structural responses. Stationary, separable modulated, and non-separable evolutionary stochastic models are used. Research efforts are focused on both linear and nonlinear structures.

Response of Linear Structures

I. Numerical analysis aspects of the Kolmogorov backward partial differential equation associated with the first-passage problem of the response amplitude of a lightly damped linear structure are considered. The structure is subjected to seismic excitation which is modeled by a broad-band stationary random process. A formula has been derived for the analytical estimation of the eigenvalues of the boundary value problem constructed by a separation of variables procedure on the Kolmogorov equation. The analytical estimates have been used as initial values in an iterative scheme which determines the eigenvalues numerically for several values of the circular barrier of the first-passage problem. An efficient algorithm for the numerical computation of the corresponding eigenfunctions has been developed. This algorithm has been used, as well, to compute the constant coefficients of a solution of the Kolmogorov equation in the form of an eigenvalues-eigenfunctions series expansion. The numerical data obtained have been examined in context with the physics of the problem. Currently, research efforts are devoted to using these analytical and numerical results as a basis for studying the first-passage problem of linear structures excited by modulated stochastic seismic models.

II. The probability density function of the response amplitude of a lightly damped linear structure subjected to a broad-band non-stationary seismic process with evolutionary spectrum is examined. In connection with this project, a combination of deterministic and stochastic averaging has been used to derive a one-dimensional diffusion equation which approximately governs the time evolution of the probability density function of the response amplitude. Based on the diffusion equation, it has been proved that the non-stationary probability density of the response amplitude can be approximated by a Rayleigh distribution with a time dependent scaling variable. An equation for the analytical determination of the scaling variable has been obtained. Currently, Monte Carlo studies are contemplated so that the reliability of this approximate result can be assessed. Furthermore, its usefulness is explored in addressing the problem of generating earthquake records which match, with specified probability, arbitrary response spectra.

Response of Nonlinear Structures

The response of a class of weakly nonlinear and lightly damped structures to a separable non-stationary stochastic seismic excitation is examined. The seismic excitation is represented as the product of a slowly varying modulating deterministic function and a broad-band stationary process. Using an averaging procedure a first order equation governing the time evolution of the response amplitude has been derived. The Fokker-Planck equation which describes the diffusion of the probability density function of the response amplitude has been considered. A particularly convenient basis of orthonormal functions, as well as necessary formulae for the determination of an approximate solution of the Fokker-Planck equation by means of the Galerkin technique, have been identified. Furthermore, based on this solution an equation has been developed for the determination of the statistical moments of the response amplitude. It is currently planned to apply this method to specific seismic models and nonlinear structures so that the significance of several engineering parameters can be better understood and properly quantified.

Acknowledgements

All of the described projects are currently supported in whole or in part by the National Science Foundation, Division of Problem Focused Research.

References

Spanos, P-T.D., "Numerical Aspects of the First-Passage Equation for the Response Amplitude of a Vibrating Linear Structure," Texas Institute for Computational Mechanics, Report TICOM 79-16, December, 1979, pp. 1-29.

Spanos, P-T.D., and Lutes, L.D., "Probability of Response to Evolutionary Process," Engineering Mechanics Research Laboratory, University of Texas at Austin, Report EMRL - 1130, September, 1979, pp. 1-21.

F. W. BARTON and T. O. WEAVER

University of Virginia

This paper summarizes current research in the Department of Civil Engineering at the University of Virginia, sponsored by the National Science Foundation, in the area of earthquake structural response of soil-structure systems using Fourier Transform techniques.

Research Objectives

The particular concern of this project is with the development and evaluation of a computational strategy for determining the earthquake response of a structure including foundation interaction effects. The frequency dependence of the dynamic properties of the soil leads to equations of motion for the soil-structure system that cannot be solved in the time domain. The usual approach is to Fourier transform the variables and solve the equations of motion in the frequency domain. The inverse Fourier transform is then used to obtain the transient response. Since the Fourier integrals are generally too complicated to evaluate, the Discrete Fourier Transform is used in which the transforms are evaluated by means of the Fast Fourier Transform algorithm.

Application of Discrete Fourier Transform techniques using the Fast Fourier Transform algorithm typically involves determining the steady state responses for a large number of excitation frequencies. For structures that have a large number of degrees of freedom, this process entails, for each frequency, a solution of a set of simultaneous algebraic equations corresponding to the number of degrees of freedom. This computational effort can be reduced somewhat by using modal analysis to reduce the numbers of degrees of freedom to something within the realm of practicality for earthquake response. Nevertheless, considerable computational effort is still required to calculate the frequency response functions.

Current efforts on this project are concerned with the evaluation of two specific alternative procedures for more efficient computation of the structural response. In the first approach, interaction effects are first determined and subsequently applied as excitation, thus reducing the soil-structure interaction problem to a fixed-base excitation problem which may be solved by standard procedures. The second approach utilizes the discrete equations in the frequency domain, but uses procedures similar to those used in structural reanalysis to avoid completely resolving the full equations at each frequency increment.

Research Approach and Results

The first alternative procedure uses modal characteristics of the fixed-base system to obtain an algebraic expression for the steady-state response of the interaction degree of freedom. Using a multistory building on a rigid foundation as an example and considering only base rotation, the equations of motion may be written as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\ (\{1\}\ \ddot{X}_g + \{h\}\ddot{\theta}) \tag{1}$$

where $\ddot{X}_g$ is the ground acceleration and θ the base rotation.

The steady-state response of the base rotation is determined by equating the base moment exerted by the structure on the foundation, to the moment resistance of the soil. Once this response is found, the rotational acceleration $\ddot{\theta}$ is known and the problem reduces to that of a base excited system in which a standard modal approach may be used. The development of this method has been completed and the accuracy demonstrated. Interaction response curves have been developed for two types of lateral reinforcing, shear beam and flexure beam. For both systems, the response is dominated by the first mode. It is anticipated that the structural response will behave in a similar manner. Two structural response terms will be considered; response at the building top and total base moment. Parameter studies will be performed to investigate the effect of relative building height and soil stiffness.

The second procedure will utilize some of the computational procedures developed for use in structural reanalysis and optimum design. Consider, for example, the problem represented by Eq. (1). The steady-state response in the frequency domain may be expressed as the product of the frequency response function {H} and the Fourier transform of the excitation. The frequency response function may be found from

$$([A] + i[B])\{H\} = \{D\} \tag{2}$$

where $[A] = ([K] - 4\pi^2 f[M])$

$[B] = 2\pi f[C]$

Traditional static structural response is governed by

$$[K]\{u\} = \{F\} \tag{3}$$

and the displacements {u} found by solving Eq. (3). In the reanalysis problem, the objective is to find the new displacements $\{u + \Delta u\}$ resulting from a new design characterized by $[K + \Delta K]$, where

$$[K + \Delta K]\ \{u + \Delta u\} = \{F\} \tag{4}$$

without completely resolving Eq. (4). Eq. (2) and Eq. (4) have the same form. Thus, determining a new frequency response function corresponding to a new frequency from Eq. (2) is equivalent to finding a new displacement resulting from new structural properties in Eq. (4). The reanalysis scheme currently being evaluated for use in the approximate solution of Eq. (2) is a combination of a Taylor series and iterative technique.

Results to date indicate that both methods described are feasible alternatives to the direct solution of Eqs. (1) and (2) and, for certain problems, offer significant savings in computational effort.

M. P. SINGH

Virginia Polytechnic Institute and State University

This note summarizes the research work being done at Virginia Polytechnic Institute and State University in the area of seismic stability evaluation of earth structures. This research work is being sponsored by the National Science Foundation.

To evaluate seismic stability of earth structures like layered foundations, slopes, embankments and dams for a prescribed design input like response spectra curves, currently time history analyses are usually performed. In these approaches, the design input is required to be defined in terms of earthquake time histories. As prescribed design spectra can only be represented by an ensemble of time histories, a large computational effort will be required to obtain reliable results by analyses for the ensemble of time histories. To avoid this problem, an approach which can use a prescribed design spectra directly and can also consider nonlinear strain dependent properties is required.

Research Objectives:

The objective of this research work is, therefore, to develop a verified analytical approach for evaluating seismic stability of materially nonlinear earth structures for seismic design inputs defined in the form of response spectra curves. A preliminary research done earlier by the investigator and his colleague [1] has identified a potentially useful approach. This approach is based on random vibration theory in which earthquake inputs could be defined in a stochastic form or by ground response spectra curves. To handle nonlinear strain dependent soil properties, the method of stochastic equivalent linearization [2] is used. In this investigation some of the assumptions made in our earlier work are being reviewed and improved. Also analytical verification of the proposed theory by simulation study is being undertaken now.

Nonproportional Damping Effects

The approach we are investigating is iterative in which in each cycle of iteration the equivalent linear soil properties are obtained and stiffness and damping matrices of the system are revised. Since it is proposed to use the ground response spectra directly, the system has to be analyzed by normal mode approach. In the normal mode approach for damped systems it is usually assumed that damping matrix is proportional. In our earlier investigation we also made the same simplifying assumption. Thus we assumed that the system damping matrix can be decoupled by the normal modes. Or in other words, the coupling terms which were obtained in the process of diagonalization of the damping matrix by the normal mode matrix were neglected in the analysis. We want to investigate the magnitude of the error introduced in the response by this assumption.

To ascertain this error, we had to come up with a method of analysis whereby the effect of nonproportional damping could be considered exactly.

We have had good luck in our investigation, as finally we have been able to develop a method in which nonproportional damping effects can be exactly included and a prescribed set of response spectra can be directly used. The approach is similar to the square-root-of-the-sum-of-the-squares type of approach, which is commonly used to obtain the design response by response spectrum approach.

We are in the process of applying this method to our problem to ascertain the magnitude of error due to the proportional damping assumption. If the response results by exact and approximate methods of analyses are significantly different in any iteration, we may have to adopt the exact method in final stability calculations. This will no doubt increase the computer cost, but it will still be cheaper than using the time history analysis approach.

Validation of Proposed Approach

It is proposed to compare the results obtained by the proposed approach with those obtained by an available truly nonlinear approach [3] for an equivalent ensemble of time histories. To obtain truly nonlinear response results, program CHARSOIL [4] developed by Professors Streeter, Wilie and Richart at the University of Michigan will be used for a layered soil strata. At this moment we are writing a computer program for our approach and also putting program CHARSOIL on our computing system and making it compatible with our research requirements. We are addressing ourselves to the requirement of having compatible soil parameters in CHARSOIL and our approach. CHARSOIL uses Ramberg-Osgood type of nonlinear relationship whereas our approach is geared to material properties described by the strain dependent nonlinear curves as developed by Seed and Idriss [5].

We will compare the results for quantities like cumulative damage potential and corresponding factor of safety, maximum stress and strains and, probably, response spectra curves for a layered soil media. Possibility of using a simple earth dam model is also being considered.

We expect to finalize this work during the summer of 1980.

References:

1. Singh, M. P. and Khatua, T. P., "Stochastic Seismic Stability Prediction of Earth Dam", Proceedings of ASCE Specialty Conference in Earthquake Engineering and Soil Dynamics, Pasadena, CA, June 1978.

2. Iwan, W. D. and Yang, I. M., "Application of Statistical Linearization Techniques to Nonlinear Multi-Degree-of-Freedom Systems", J. App. Mech., 39, pp. 545-550, 1970.

3. Streeter, V. L., Wylie, E. B. and Richart, F. E., Jr., "Soil Motion Computations by Characteristics Method", Journal of the Geotechnical Engineering Division, ASCE, Vol. 100, No. GT3, March 1974.

4. Streeter, V. L., Wylie, E. B., and Richart, E. F., Jr., "CHARSOIL - Characteristics Method Applied to Soils", National Information Service - Earthquake Engineering Computer Applications, University of California, Berkeley, CA, March 1974.

5. Seed, H. B. and Idriss, I. M., "Soil Moduli and Damping Factors for Dynamic Response Analysis", Report No. EERC 70-10, University of California, Berkeley, CA, 1970.

INDEX OF AUTHORS OF WRITTEN SUMMARIES

MAILING LIST INFORMATION

Due to the ever expanding size and frequent changes in the UCEER mailing list, no printed copy of the mailing list is included as part of this volume. Copies of the mailing list will be made available to organizations and individuals having a need for this information. Requests for copies of the mailing list should be addressed to:

UCEER
Mail Code 104-44
California Institute of Technology
Pasadena, California 91125

A nominal charge will be made for postage and handling.