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Laboratory tests of two new strong-motion accelerographs have resulted in significant improvements in accuracy and reliability. A new manually operated vibration test table with long period and permanent displacement capabilities has made it possible to extend studies of accelerograph accuracy. Contributions have been made to improvements in the Southern California Strong-Motion Accelerograph Network by supplying additional instruments and through studies of optimum location. In cooperation with the U. S. Coast and Geodetic Survey improved methods for data processing of accelerograms have been worked out, and significant progress has been made towards a uniform treatment of past earthquake records. An improved set of artificial earthquake accelerograms based on statistical studies of past records has been produced which will facilitate structural dynamics and soils investigations. Computer studies of yielding systems have been extended to include more realistic damping conditions, and digital computer models for prestressed concrete beams have been developed. Structural dynamic tests of full scale structures have been carried out for a multi-story building and for a rockfill dam. Interaction effects in yielding structures loaded simultaneously in several directions have been examined. Soil dynamics studies have concentrated on soil-structure interactions. Calculations of dynamic response of structures founded on an elastic half-space have defined the conditions under which higher modes of vibration can be neglected. The earthquake response of a flexible retaining wall has been investigated.

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A Comprehensive Research Program in Earthquake Engineering

Summary

Laboratory tests of two new strong-motion accelerographs have resulted in significant improvements in accuracy and reliability. A new manually operated vibration test table with long period and permanent displacement capabilities has made it possible to extend studies of accelerograph accuracy. Contributions have been made to improvements in the Southern California Strong-Motion Accelerograph Network by supplying additional instruments and through studies of optimum location. In cooperation with the U. S. Coast and Geodetic Survey improved methods for data processing of accelerograms have been worked out, and significant progress has been made towards a uniform treatment of past earthquake records.

An improved set of artificial earthquake accelerograms based on statistical studies of past records has been produced which will facilitate structural dynamics and soils investigations. Computer studies of yielding systems have been extended to include more realistic damping conditions, and digital computer models for prestressed concrete beams have been developed. Structural dynamic tests of full scale structures have been carried out for a multi-story building and for a rockfill dam. Interaction effects in yielding structures loaded simultaneously in several directions have been examined.

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of vibration can be neglected. The earthquake response of a flexible retaining wall has been investigated.

A Comprehensive Research Program in Earthquake Engineering

Research Investigations

The research investigations under the grant will be summarized under the three headings used in the original proposal in the first annual report: I, Strong-Motion Seismology; II, Structural Dynamics, and III, Soil and Soil-Foundation Dynamics.

I. Strong-Motion Seismology

A. Instrumentation

1.) A special vibration test table was designed which permits under manual control the introduction of long period and permanent displacement components into the motion. The displacement of the table is measured versus time, and can be directly compared with double-integrated acceleration records. Tests made on the RFT 250 Strong-Motion Accelerograph have revealed basic difficulties in the determination of long period motions and permanent displacements.

2.) Additional tests have been made on the random vibration table comparing measurements on a high-frequency laboratory accelerometer with those recorded on RFT 250, RMT 280, and MO 2 Strong-Motion Accelerographs. Based on a comparison of calculated Fourier Spectra, it was concluded that all three instruments were correct within a digitizing error.

3.) Tests were made of the accuracy of the electronic timing system in the RFT 250 Strong-Motion Accelerograph which showed that accuracy was suitable for the intended applications.

4.) Charge-discharge tests were made of the new lead-lead dioxide cells used in the RFT 250 and RMT 280 strong-motion accelerographs. Studies were made of instrument behavior at reduced voltage corresponding to various discharge periods.

5.) Long term stability tests were made of the electronic circuitry in the RMT 280 Magnetic Tape Accelerograph. Included was an evaluation of delay time in starting under various repetitive operating conditions.

6.) Preliminary design was done on a test system suitable for field servicing of the RMT 280 Magnetic Tape Accelerograph.

7.) Tests of accuracy of electronic analog to digital conversion of earthquake ground acceleration records were made using equipment in the Caltech computing center.

8.) The Borrego Mountain earthquake offered the most complete test so far on the reliability of the strong-motion accelerograph network in Southern California. Only one instrument malfunction occurred out of 120 triggered accelerographs. In cooperation with the U. S. Coast and Geodetic Survey, a report was issued reproducing all accelerograph and seismoscope records from this earthquake.

9.) Based partly on network gaps revealed by the Borrego

Mountain earthquake, several additional RFT 250 optical recording accelerographs have been procured for permanent field installation. Several accelerometers have also been obtained for temporary installation in field stations operated by the Caltech Seismological Laboratory.

10.) Special RFT 250 optical type accelerometers were ordered having (a) improved pivot suspension for transducer element, and (b) supplementary vertical electrodynamic starter system.

11.) Studies have been made of the feasibility of direct telephone links between accelerographs to provide simultaneous starting. In this way the time delays inherent in wave propagation paths of several miles length can be used to start certain accelerographs prior to the arrival of strong ground motion.

12.) Special transducer-amplifier equipment suitable for microtremor measurements and for structural vibration measurements has been ordered.

B. Data Processing

1.) About 150 strong motion accelerograms from past earthquakes have been prepared in archival form. Original photographic records were obtained from the USCGS in Washington, and full size contact film negatives were made at the Seismological Field Survey in San Francisco. From these negatives, contact positives on translucent film were then made in Los Angeles for digitizing purposes. A full

set of film negatives and translucent positives is filed in San Francisco and at Caltech.

2.) About 30 earthquake accelerograms from the above file have already been digitized in standard form on a Benson-Lehner 099 Data Reducer. All three components have been digitized on an unequal time basis suitable for machine processing. Work is now in progress to complete the digitization of all past records.

3.) A detailed study has been completed of optimum data processing techniques for digitized accelerograms, and standardized procedures have been established, including:

(a) Evaluation of digitizing errors, for single and multiple operators.

(b) Base line correction techniques, and accuracy of integrated velocity and displacement curves for various frequency ranges.

(c) Calculation of Fourier Spectra and Response Spectra.

(d) Effects of such variables as record length, initial and terminal points, etc., on response calculations.

4.) A special study has been made of the digital processing of seismoscope data using modern filtering and smoothing techniques. It has been shown that such techniques permit the recovery of a missing accelerogram component from the array of accelerograph data obtained during the Parkfield earthquake.

C. Strong-Motion Earthquake Statistics

1.) Studies of the statistical properties of strong ground motion such as occurrence in time, duration, maximum acceleration, energy, and attenuation with distance have been up-dated, and prepared in a form suitable for engineering design applications.

2.) A new set of artificial earthquake accelerograms for a series of simulated earthquake motions has been prepared. Ground acceleration records have been digitally synthesized which model characteristics of different types of strong earthquake ground motion. The artificial accelerograms are sections of stationary random processes with a prescribed power spectral density multiplied by envelop functions chosen to model the changing amplitudes at the beginning and end of the accelerogram.

3.) In cooperation with the Caltech Seismological Laboratory, statistical studies of the frequency of occurrence of earthquakes in Southern California have been up-dated and a new statistical model has been developed. This new model gives an excellent fit to the basic data, and directs attention to some new aspects of basic mechanisms of earthquakes.

4.) An analysis is being made of earthquake ground motions recorded at the San Onofre Nuclear Power Plant of the Southern California Edison Company. The Borrego Mountain earthquake of 9 April 1968 provided the first earthquake recording made at a nuclear power plant, and a report is

being prepared in cooperation with SCE engineers describing the plant and the recorded ground motions.

D. Local Seismicity Studies

1.) Studies are being made of the influence of the properties of the ground on the surface motions of the ground during earthquakes. These analytical investigations involve layered models including energy dissipation effects, and transient motion inputs.

2.) Theoretical studies of simplified local geological models for microtremor interpretations are being made. Models involving primarily horizontal propagation such as for surface waves are being compared with more common solutions for vertically arriving waves.

3.) Additional studies have been made of optimum distribution of strong-motion accelerographs in the Southern California region with the aim of completing the network in the most effective way. It is planned that certain older accelerographs in the Los Angeles area be relocated to improve coverage.

E. Mechanics of Faulting

In cooperation with the Caltech Seismological Laboratory a study has been made of the 1940 El Centro earthquake as a multiple event. By analyzing low magnification teleseismic data using modern filtering and data processing techniques, the sequence of events at El Centro has been worked out in detail. In view of the importance of this El Centro earthquake to engineers, because it provided the most severe ground acceleration record so far measured, it is important to understand the details

of the event.

II. Structural Dynamics

1.) A theory of yielding in framed structures incorporating effects of inelastic interactions has been developed. The dynamic response of a simple space frame is under investigation considering inelastic interactions between axial forces and biaxial bending moments.

2.) A method of using a distributed element representation of hysteretic systems for transient response studies has been developed, and the implications of the approach for earthquake problems have been explored.

3.) Dynamic properties of typical tall buildings such as natural frequencies and mode shapes have been correlated with building height. Simplified relationships useful for preliminary design purposes have been established.

4.) In cooperation with the staff of Teledyne Earth Sciences a complete set of ambient vibration measurements were made on a new multi-story building in Los Angeles. Detailed calculations of building characteristics were available for correlation, as well as building periods measured during the Borrego Mountain earthquake of 9 April 1968 by accelerographs permanently installed in the building.

5.) The dynamic response of a 20-story prestressed concrete frame to earthquake excitation was studied using digital computer techniques. A special beam model was developed

suitable for computer representation of the characteristic behavior of prestressed beams.

6.) In cooperation with staff from the University of Mexico and the University of California at Los Angeles, vibration generator tests were made of the Infiernillo Dam in Mexico. Two synchronized vibration generators and complete instrumentation were transported to the site in Mexico, and complete studies of frequencies and mode shapes were carried out.

7.) Computer studies were made of the plastic yielding of a 20-story steel frame structure subjected to earthquake excitation. These studies, which extended the work of Giberson reported last year, have involved both interfloor and mass-proportional damping, and have included a comparison of yielding response with linear response in a non-yielding system.

III. Soil and Soil-Foundation Dynamics

1.) A computer program has been developed to study the soil structure interaction problem using a finite element approach. The problem of the response of a flexible retaining wall to earthquake exciting forces is under investigation.

2.) Theoretical studies are being made of the dynamics of building structures founded on an elastic half-space. Results indicate that effects of modes higher than the first are usually very small. The analysis is to be used to

interpret the complete vibration tests of the 9-story Millikan Library on the Caltech campus, which included many measurements of foundation soil responses.

IV. Special Studies

A numerical model for the study of tsunami run-up has been developed based on a discrete element approach. Such dissipation forces as bed friction are accounted for in the calculations. It is hoped that such analytical investigations can be correlated with field data and the experimental results of model tests.

Publications and Reports

Iwan, W. D., "The Distributed Element Concept of Hysteretic Modeling and its Application to Transient Response Problems", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Housner, G. W., "Engineering Estimates of Ground Shaking and Maximum Earthquake Magnitude", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Spencer, R. A., "The Nonlinear Response of a Multistory Prestressed Concrete Structure to Earthquake Excitation", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Nigam, N. C. and Housner, G. W., "Elastic and Inelastic Response of Framed Structures During Earthquakes", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Hudson, D. E., Nigam, N. C. and Trifunac, M.D., "Analysis of Strong-Motion Accelerograph Records", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Jennings, P. C., Housner, G. W. and Tsai, N. C., "Simulated Earthquake Motions for Design Purposes", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Jennings, P. C., "Spectrum Techniques for Tall Buildings", 4th World Conference on Earthquake Eng., Santiago, Chile, 1969.

Jennings, P. C. and Husid, R., "Collapse of Yielding Structures during Earthquakes", Jour. Eng. Mech., ASCE, Oct. 1968.

Jennings, P. C. and Kuroiwa, J. H., "Vibration and Soil-Structure Interaction Tests of a Nine-Story Reinforced Concrete Building", Bull. Seis. Soc. Amer., vol. 58, no. 3, June, 1968.

Spencer, R. A., "Stiffness and Damping of Cyclically Loaded Prestressed Members", 2nd Mexican Congress on Earthquake Eng., Vera Cruz, May, 1968.

Giberson, M. F., "Two Nonlinear Beams with Definitions of Ductility", accepted for Jour. Str. Div., ASCE, 1968.

Giberson, M. F., "Maximum Response Ranges of Nonlinear Multi-Story Structures Subjected to Earthquakes", accepted for Bull. Seis. Soc. Amer., 1968.

Nigam, N. C., "Yielding in Framed Structures Under Dynamic Loads", accepted for ASCE Annual Meeting, October, 1968.

Spencer, R. A., The Nonlinear Response of a Multistory Prestressed Concrete Structure to Earthquake Excitation, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, July 1968.

Nigam, N. C. and Jennings, P. C., Digital Calculations of Response Spectra From Strong Earthquake Records, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, June 1968.

Jennings, P. C., Housner, G. W. and Tsai, N. C., Simulated Earthquake Motions, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, April 1968.

Cloud, W. K., Hudson, D. E. and Brady, A. G., Strong Motion Instrumental Data on the Borrego Mountain Earthquake of 9 April 1968, Seismological Field Survey, U. S. Coast and Geodetic Survey, and Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, August 1968.

Professional Staff

The following professional personnel have received support in various degrees from the research grant.

Principal Investigators

T. K. Caughey, Professor of Applied Mechanics

G. W. Housner, Professor of Civil Engineering and Applied Mechanics

D. E. Hudson, Professor of Mechanical Engineering and Applied Mechanics

W. D. Iwan, Associate Professor of Applied Mechanics

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R. F. Scott, Professor of Civil Engineering

Post-Doctoral Research Fellows

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N. C. Nigam (Ph.D., Caltech, 1967)

R. A. Spencer (Ph.D., Univ. Auckland, 1966)

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Related Activities

1. As a part of a general study of the Caracas earthquake for the National Academy of Engineering, the following paper was prepared: Jennings, P. C. and Tsai, N. C., "Intensity of Ground Motion in the Caracas Earthquake of July 29, 1967".

2. G. W. Housner was a member of an ASCE Power Division Panel on Earthquake Safety of Nuclear Power Reactors, meeting in September 1968 at Washington State University.

3. G. W. Housner and D. E. Hudson have been involved in the planning for the Fourth World Conference on Earthquake Engineering to be held January 1969 at Santiago, Chile, as members of papers committee and session chairmen in Inelastic Response of Structures and in Ground Motions and Instruments.

4. G. W. Housner has continued to participate as a member of the State of California Earthquake Advisory Board, which is primarily concerned with the safety of the California water project.

5. With Caltech support, R. A. Spencer attended the 2nd Mexican Congress on Earthquake Engineering, Vera Cruz, and presented a paper on the earthquake response of prestressed concrete frames.

6. J. Bielak attended a special conference on Wave Propagation in

Soils and Properties of Granular Materials arranged by the Soil Mechanics Division of ASCE and NSF at the University of New Mexico.

7. D. E. Hudson participated in a one-hour television program on Earthquake Hazards on the U.S. Educational T.V. Network, along with Professor C. R. Allen of the Division of Geological Sciences.

8. At a two-day conference and field trip in the San Francisco area for the Caltech "Earthquake Research Affiliate" program, G. W. Housner and D. E. Hudson presented talks on the Koyna, India, earthquake.

9. As a member of the Seismology Committee of the National Academy of Sciences, D. E. Hudson participated in working group sessions preparing the forthcoming report on "Seismology: Retrospect, Current State, and Outlook".

10. G. W. Housner, D. E. Hudson, R. F. Scott and P. C. Jennings, as members of the National Academy of Sciences Committee on the Alaska Earthquake, have completed specialized papers and are engaged in editorial duties in the preparation of the final published report of the Engineering Panel, which is to appear in three volumes.

11. D. E. Hudson and R. F. Scott have completed specialized chapters in a special report on Earthquake Engineering Research being prepared for the National Academy of Engineering under the chairmanship of G. W. Housner.