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BEHAVIOUR OF UNDERGROUND LIFELINES IN SEISMIC ENVIRONMENT

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Interim Grant Report No. IR-4

Prepared for
National Science Foundation (RANN Branch)
1800 G Street
Washington, D.C. 20550

Grant No. ENV P76-9838

JULY 1977

25

BIBLIOGRAPHIC DATA SHEET	1. Report No. NSF/RA-770315	2.	3. Recipient's Accession No.

4. Title and Subtitle
Behavior of Underground Lifelines in Seismic Environment
(Interim Grant Report No. IR-4)

5. Report Date
July 1977

6.

7. Author(s)
P. Weidlinger

8. Performing Organization Rept. No. IR-4

9. Performing Organization Name and Address
Weidlinger Associates, Consulting Engineers
110 East 59th Street
New York, NY 10022

10. Project/Task/Work Unit No.

11. Contract/Grant No.
ENVP769838

12. Sponsoring Organization Name and Address
Research Applied to National Needs (RANN)
National Science Foundation
Washington, D.C. 20550

13. Type of Report & Period Covered
Interim

14.

15. Supplementary Notes

16. Abstracts

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17. Key Words and Document Analysis. 17a. Descriptors

Earthquakes
Pipes (tubes)
Line pipes
Pipelines
Piping systems
Seismology
Earthquake resistant structures

17b. Identifiers/Open-Ended Terms
Underground lifelines

17c. COSATI Field/Group

18. Availability Statement NTIS	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 25
	20. Security Class (This Page UNCLASSIFIED	22. Price PC A02/MF A01

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

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ABSTRACT

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For purposes of risk analysis, optimalization and cost-benefit studies of existing or planned systems, covering large areas, a statistical method is developed which provides the expected value of free field gradients, as affected by subsurface and geology. These gradients are used to estimate the probable performance of the system during an earthquake defined by a Power Spectral Density function.

INTRODUCTION

The purpose of this research is to develop procedures for:

a. analysis and design of underground lifelines,

b. evaluation and risk analysis of existing or planned systems and,

c. the upgrading of existing installations.

Because a major objective is to achieve results as early as possible and to present them in a manner that is acceptable to the ultimate users, i.e., engineers, utilities and policy-making bodies, it was necessary to restrict the initial phases of the investigation. It was decided to limit this phase to water distribution systems, which constitute a vital and extensive part of lifelines. The main effort is centered on pipes of about 20" diameter or less, because these make up the major portion of typical water distribution systems, and because their behaviour during earthquakes is less well understood than the behaviour of large diameter transmission lines and feeder mains. These limitations make it possible, within the proposed time frame, to develop a general theory and methodology, and to test and illustrate its application.

To achieve these objectives within the current phase of the grant, a series of simultaneous investigations were initiated. While most of these are not, as yet, completed (in fact, some are at an initial phase), sufficient progress has been made to issue a series of interim grant reports, papers and research memoranda. In this report, these investigations are briefly summarized, including the major conclusions and anticipated findings.

The interaction between these studies is also discussed, but for further details, the reader is referred to the documents listed in the Appendix.

LITERATURE

There exist, a rapidly growing body of literature addressed to the various aspects of the lifeline problem, indicating the increasing awareness of the scientific and engineering community of the need for analytical and design tools. In the following paragraphs, a brief summary of the bibliographic references, which were used in the reports and papers listed in the Appendix, is provided. The literature may be classified by six major topics:

1. Free Field Phenomena: This group contains papers which consider those characteristics of ground motion which have special relevance to the behaviour of underground pipelines. e.g., relative motions of spatially separated points, cross correlation of motions, phase velocity phenomena, effects of local geological characteristics. Many of these papers contribute to the clarification of the deterministic and statistical definition of the spatial and temporal variation of the displacement field. Observation of simultaneous motions recorded by instrument arrays have also been published.

2. Experimental Results: There are two categories:

   (a) Literature on the behaviour and physical properties of pipes of different materials (steel, ordinary and ductile cast iron, concrete and plastics) and on materials used in the joints (cement, lead, rubber). These are static experiments, clarifying the behaviour under ordinary service conditions. More recently, in Japan, dynamic experiments were conducted on the behaviour of joints, to explore dissipative and other dynamic characteristics.

(b) A second set of experiments (also in Japan) address themselves to interaction phenomena between pipes and surrounding backfill, to determine the intensity and frequency dependence of frictional forces.

3. Analytical Work and Design Recommendations: Some of the work in this area is directed towards the behaviour of long, slender, buried structures, which deform in conformity with long wavelength ground displacements. The results are applicable to large diameter, very long continuous structures such as tunnels and large pipelines, and are based on calculations of static strains due to extension and curvature. These studies lead to recommended design procedures for such structures and they have been extended to the case of pipelines subjected to large displacements caused by fault movements. Discrete analytical models are also used to simulate the behaviour of underground pipes and the required parameters are determined by the previously discussed static and dynamic experiments. The model is subjected to an excitation which simulates earthquake motion. Recently, extensive and detailed tentative analytical and design recommendations, applicable to oil pipelines, have been issued in Japan. A summary translation of this work is contained in a Research Memorandum, listed in the Appendix.

4. Post Earthquake Surveys and Statistical Interpretation: Numerous papers report and tabulate the damage to underground utilities. There are attempts to correlate damage to magnitude, and to geological and subsurface conditions. Such surveys are available for nearly all recent seismic events of significance.

5. Risk Analysis: There are several papers on risk analysis of structures in seismic environment. Only a few are directed specifically to underground lifelines, but this subject is also mentioned in recent books on seismic analysis. These researches are addressed to general methodology; quantified conclusions or examples are not available primarily because of lack of deterministic or statistical inputs.

6. Static Design and Analysis of Underground Pipes: There is extensive literature providing practical information regarding the design of joints, connections and the selection of wall thickness of pipes in various materials, for various laying conditions. Many design tables and handbooks are published by manufacturers.

DATA BASE

1. Physical Properties of Pipe Networks: Because one purpose of the work is to determine the safety and serviceability of underground lifelines, the first task was to develop failure mechanisms, failure criteria and useful service limits. This was done by examining the current design practice used in water line design and by adopting some of the applicable criteria, and by supplementing these with experimental data. The

results can be conveniently presented in form of a "Damage Matrix" * which shows the maximum value or range of permissible displacements or stresses. The matrix has the form shown below:

TABLE 1

DAMAGE MATRIX (Failure - Leakage)

	Axial Displacement: Compression	Axial Displacement: Tension	Curvature (bending)	Rotation (torsion)	Transverse Displacement (shear)
Joints					
Connections					
Pipes					
Other Details					
.					
.					
.					

The matrix is formulated separately for failure (breakage) and service limit (leakage) for various types of materials, sizes, etc. To accomplish this, a general survey was made of the following subjects:

Pipe materials and their properties;
Sizes (diameter, wall thickness, length);
Joint types and packing materials;
Laying conditions;
Design practices and criteria;
Factors of safety.

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* The matrix is, at the present, incomplete, for lack of experimental data, but is adequate to demonstrate the methodology.

The development of the Damage Matrix also provides information regarding the stiffness of pipes and joints. These are used in the analytical models to obtain force-displacement functions and information regarding energy dissipating properties.

2. Questionnaire Survey: To define the current practice and to benefit from the practical experience of users and designers, a questionnaire survey was conducted among utilities within the United States. The response to this survey disclosed the degree of perception of seismic risk of the utilities and their current practices of dealing with the problem. The survey showed the prevalent use of steel pipes with rubber gasket joints in new transmission lines and confirmed that distribution lines were mainly in cast iron with a variety of caulking compounds used in the joints. It also provided information on current laying practice, damage experiences and repair procedures.

The investigations and survey had additional benefits, by indicating the current technology in water distribution systems; this is essential to the development of realistic parameters in analytical models. In turn, it has made the utilities aware of our interest and has helped to establish useful working relations with their technical staff.

3. Modeling: It is clear that, because of the large variety of the relevant characteristics of water lines, response to seismic excitation will exhibit a broad range of behaviour.

At one extreme are large steel pipes with welded joints, which, depending on their diameter and wall thickness, may be modeled as slender elastic beams or as long cylindrical shells. Large diameter prestressed concrete transmission lines may also be modeled this way. Failure will most likely be governed by strength (stress) or instability (buckling) criteria.

At the other extreme, we find pipes with deformable joints (elastic and inelastic). The relatively short, (about 20 ft) small diameter pipe sections may be modeled as rigid links connected by elastic or inelastic hinges. Damage criteria should most likely be expressed in terms of deformation. A list of the anticipated analytical models is shown in the table below.

TABLE 2

ANALYTICAL MODELS - (Failure Modes)

Diameter	Continuous or Rigidly Connected Pipes	Pipes with Flexible Joints
Small	Slender elastic beam (strength/instability failure)	Rigid links with elastic or inelastic hinges (deformation failure)
Large	Long cylindrical shell (strength/instability failure)	Short cylindrical shells with elastic or inelastic connections (strength) instability, failure)

4. <u>Causes of Damage</u>: Post-earthquake surveys disclose two major causes of damage:

a) due to large displacements, in pipes crossing fault planes, and

b) due to the smaller amplitude shaking in pipes, distant from the epicenter.

The treatment of these two cases is distinct. The first case is one of an imposed large displacement analizable with few assumptions. The second one turns out to be more difficult. There is some evidence in post-earthquake surveys that the most frequent damage is due to axial displacement resulting in separation at the joints. A smaller, but still significant, number of incidences of damage is observed due to transverse displacement. These observations become plausible if we estimate free field strains and curvature occuring at locations of low shear velocity, subjected to high intensity shaking (e.g., Zones 3 and 4). Such rough estimates give typical peak free field strains of

$$\varepsilon = 10^{-2} \text{ to } 10^{-3}$$

and free field curvatures of

$$\kappa = 10^{-5} \text{ to } 10^{-6} \text{ ft}^{-1}$$

The strain is in excess of the failure strain of most pipes but the curvature is lower than the failure curvature of small diameter pipes.

Reports of post-earthquake surveys in Japan indicate a correlation between damage and Richter Magnitude, but modified by subsurface conditions: There appears to be a concentration of damage in regions where there is a transition in subsurface materials or of geological formations. These observations are borne out, to some extent, by U.S. data which show that subsurface conditions have different effects on underground pipes than on conventional aboveground structures. It appears that lack of homogeneity plays an important role in the vulnerability of underground lifelines.

METHODOLOGY AND RESEARCH PROGRAMS

The information acquired through literature search and the data base, point to three separate but closely related problems of the underground lifeline research:

1. Seismic Environment: The initial definition of the seismic environment is given by:

   a) a postulated Magnitude of the earthquake,
   b) return period associated with the Magnitude,
   c) hypocentral distance, and
   d) local geology, subsurface materials and layering.

Current engineering seismology is largely directed towards the problem of the dynamic response of essentially aboveground buildings and structures. The response to seismic excitation is assumed as temporally and spatially coherent over the entire surface occupied by the building. The frequency domain of the excitation is defined with the response frequency range of these structures in mind.

This definition of the environment must be reformulated and adapted to the lifeline problem. Lifelines typically extend over long distances, which are also large compared to the diameter of the components. The mass of typical components is much smaller than that of most buildings and consequently they may be expected to respond at other frequency ranges.

The primary problem of the environment (free field) is the definition of relative motion of spatially separated points. The customary current assumption of engineering seismology, that of a one dimensional coherent (in-phase) wave form propagating vertically from the base rock, is not quite suitable for the determination of relative motions of separate points at or near the surface. Significant relative motions do appear to exist and are caused by:

a) the time difference in the arrival of waves propagating (in the direction of axis of pipes) with appropriate local phase velocities in the soil layer above the rock base, and by

b) changes in wave forms (frequency and amplitude) due to changes in geology (slope or abrupt change of base rock) and/or variation of the properties of the soil layers.

The effects of these phenomena may be treated deterministically if complete and detailed subsurface information is available. But if the information contains uncertainties, and is available in a sample form over larger areas, the treatment is statistical and the results are probabilistic. In many instances, the information will be somewhat incomplete and a combination of the deterministic and probabilistic features of the free field must be used.

The free field problem for lifelines requires the processing of records and, if feasible, an extension of the frequency range, by determining

a) local phase velocities in the soil, and

b) the deterministic and statistical correlation of the motion of spatially separate points.

If this information is available, relative motion of separate points, as well as strain and curvature components as a function of frequency (or wave length), can be calculated.

These subjects are currently being explored, and they may be resolved to varying degrees of detail, within the current phase of the work.

2. Component Design: If the seismic environment is sufficiently defined (deterministically and/or statistically) the analysis of underground pipelines is a relatively straightforward, although complex, task. The appropriately processed free field record is used to determine the displacement field and its higher derivatives (gradients) such as components of strain and curvature in the region of interest. Apriori there are two relevant response characteristics for underground pipelines:

a) Weak interaction exists if the system largely conforms to the displacement field, although its motion may be modified by frictional losses and slippage. Such behaviour is anticipated in response to low frequency (long wave length) components of the excitation. Because of the (partial) conformity of the system with the displacement field, the deformed shape of the components may be determined if the free field gradient is known and, therefore, the performance in terms of displacement or stresses is directly obtainable. It is anticipated that there is a class of components which respond primarily in this manner.

b) Strong interaction implies a dynamic response to the displacement field. To determine the response characteristics, the pipes and the surrounding soil may be represented by a finite element model. The model is subjected to periodic excitation at various frequencies to determine its response characteristics. The model is used to determine the (frequency dependent) virtual mass, stiffness and radiation damping effects.

These quantities are utilized in a (computationally economical) discrete model, consisting of rigid (or elastic) links of appropriate mass-density, interconnected by elastic (or inelastic) springs and reacting on discrete springs and dashpots representing the surrounding medium. This model is used to determine the significant mode shapes and frequencies (if such exist) of the system. The result of a series of such calculations may be presented in a table of "Typical Dynamic Parameters" of pipes of various dimensions, with various joint materials and laying conditions.

The information can be presented conveniently in form of a modified response spectrum, called "Interference Response Spectrum." It gives the algebraic difference of the peak absolute displacement amplitude vs. frequency of two spatially separated mass points, interconnected by an elastic (or inelastic) spring and dashpot. The two spatially separated mass points are subject to simultaneous ground excitation by the displacement field at the two locations, and the response depends on the interference of the two wave forms. The separation distance represents the length of the pipe sections between flexible joints. In case of pipes embedded in a homogeneous elastic medium, the excitation is the algebraic difference of the amplitudes caused by a phase difference Δt, defined by

$$L = c\Delta t$$

where L is the distance between joints and c is the local shear wave phase velocity. The Interference Spectrum in this case is represented by a family of curves, associated with parameters Δt. Such spectra will also be constructed to show the response to spatial variations resulting from both frequency and amplitude shifts (i.e., change of wave form) caused by variations of geology, subsurface layers or random effects.

The Interference Response Spectrum is used to obtain the peak amplitude response of the buried pipe for each significant mode shape and frequency, which are then appropriately combined to give the total response. This procedure, familiar to engineers, is applicable to both strong and weak interaction, but in the latter case the spectral amplification will be close to unity.

This technique, in conjunction with the Damage Matrix and a table of Dynamic Parameters for various types and sizes of pipes with a variety of laying conditions, should provide a useful and straightforward tool for the design and evaluation of lifeline system components.

3. System Analysis: The procedure described above is designed mainly for systems components, such as single pipe runs or small networks. (A study of such networks has shown that there is only a limited interaction between distant components). It is in principle, applicable to larger systems, but the calculations are detailed and unnecessarily time consuming. In large regions, there will be insufficient subsurface data and detailed information on existing or planned systems will not be available in most cases for evaluation, risk analysis, optimalization and cost-benefit studies.

For these purposes, a separate approach is developed. Subsurface data samples over a large region are obtainable by examining boring logs at grid points. The ground properties at grid locations are identified by a single quantity such as the predominant ground frequency and its statistical parameters (mean value, variance and correlation distance). For a postulated earthquake defined by the power spectral density of the acceleration, the expected value of the free field strain (and possibly curvature) may be evaluated. An approximate relationship between such free field gradients and average damage can be developed from the component studies and the damage matrix. The expected performance of a large system for which only incomplete information is available, can be calculated by this process. This will provide the basis for quantified risk analysis by predicting the extent of expected damage.

* * * * * * * *

CONCLUSIONS AND RECOMMENDATIONS

It is anticipated that at the conclusion of the first phase of this research, early in 1978, many of the significant aspects of the problem will have been identified and clarified. The analytical and design methodology will be sufficiently developed to outline a simplified procedure, and apply it to an illustrative example of design and risk analysis. The inter-relationship between the various aspects of the ongoing research effort, leading to these results, is shown on the flow chart, Figure 1.

Our current work has called attention to the need for an extension and deepening of the information on the physical properties of the pipeline components, so that the Damage Matrix can be expanded to include most relevant materials and details. This information can only be acquired by experimental techniques.

Similarly, the definition of the parameters of dynamic soil-pipe interaction must be confirmed and extended by laboratory experiments conducted with pipe components embedded in various soil media, subjected to time dependent loading in relevant frequency ranges.

The reliability of the analytical work may be tested and improved by conducting larger scale simulation experiments, using H.E. or nuclear explosive sources for ground excitation. The problem of the seismic environment turns out to be more difficult and elusive than anticipated.

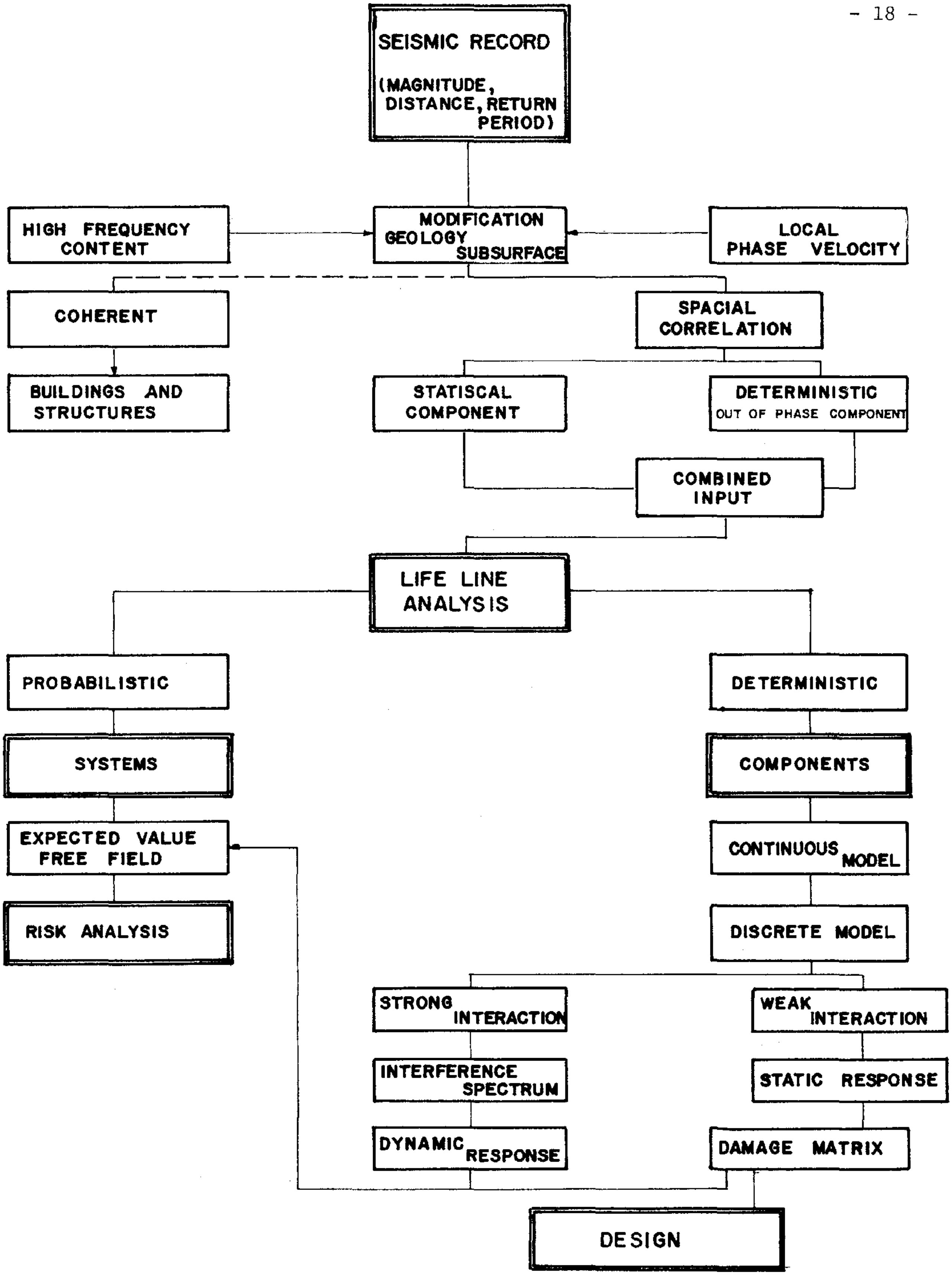
SEISMIC RECORD
(MAGNITUDE, DISTANCE, RETURN PERIOD)
HIGH FREQUENCY CONTENT
MODIFICATION GEOLOGY SUBSURFACE
LOCAL PHASE VELOCITY
COHERENT
SPACIAL CORRELATION
BUILDINGS AND STRUCTURES
STATISCAL COMPONENT
DETERMINISTIC OUT OF PHASE COMPONENT
COMBINED INPUT
LIFE LINE ANALYSIS
PROBABILISTIC
DETERMINISTIC
SYSTEMS
COMPONENTS
EXPECTED VALUE FREE FIELD
CONTINUOUS MODEL
RISK ANALYSIS
DISCRETE MODEL
STRONG INTERACTION
WEAK INTERACTION
INTERFERENCE SPECTRUM
STATIC RESPONSE
DYNAMIC RESPONSE
DAMAGE MATRIX
DESIGN

FIGURE 1

Experiments with explosive sources will contribute to the clarification of some crucial details, but a substantial amount of analytical research is needed to develop specific information which constitutes the basic input to analysis and design.

The acquisition of information as outlined above is needed to achieve all of the objectives of the program. The work will be extended to consider pipelines for oil and gas and to vehicular and railroad tunnels. This will require investigation into procedures for larger diameter pipes. Effects of large displacements associated with fault movements will also be considered.

Application examples need to be tested on a wider range and variety of components and systems. After sufficient experience is obtained in application, it will be appropriate to initiate the development of tentative design procedures and criteria which will form the basis of design manuals and guidelines to be used by civil engineers and utilities.

A summary of future research is given in the table below:

TABLE 3

FUTURE RESEARCH

(3 years)

1. Design and Monitor Experimental Investigations
    - a) Soil-pipe interaction.
    - b) Dynamic behaviour of joints.
    - c) Explosive source simulations.
2. Free Field

    Develop definition specifically applicable to underground lifeline problems.
3. Extension to Other Lifelines
    - a) Gas.
    - b) Oil.
    - c) Vehicular and RR tunnels.
4. Extension of Current Effort
    - a) Application of analysis and design methodology to a range of components (materials, joints, details).
    - b) Application of risk analysis methodology to representative systems.
    - c) Procedure for large diameter pipes.
    - d) Procedure for large amplitude ground displacements (fault motion).
5. Draft Design Procedures

    To be used to initiate work on design code recommendation.

APPENDIX

PUBLISHED PAPERS

P-1 "Underground Pipelines In A Seismic Environment", by J. Isenberg, P. Weidlinger, J.P. Wright and M.L. Baron, Weidlinger Associates, Proceedings, Specialty Conference on the Current State of Knowledge of Lifeline Earthquake Engineering, August 30-31, 1977, U.C.L.A., T.C.L.E.E., American Society of Civil Engineers.

P-2 "Underground Pipe Damages and Ground Characteristics", by Masanobu Shinozuka and Hideji Kawakami, Columbia University, Proceedings, Specialty Conference on the Current State of Knowledge of Lifeline Earthquake Engineering, August 30-31, 1977, U.C.L.A., T.C.L.E.E., American Society of Civil Engineers.

INTERIM GRANT REPORTS

IR-1 "Survey of Existing Underground Water Pipelines With Emphasis on Their Seismic Resistance", by J. Isenberg and J.P. Wright, Weidlinger Associates, Grant P76-9838, Interim Grant Report No. 1, July 1977

IR-2 "Development of Interference Response Spectra For Lifeline Seismic Analysis", by I. Nelson and P. Weidlinger, Weidlinger Associates, Grant P76-9838, Interim Grant Report No. 2, July 1977

IR-3 "Water Distribution Systems (Physical Characteristics and Design Methodologies)", by M.G. Salvadori and A. Singhal, Weidlinger Associates, Grant P76-9838, Interim Grant Report No. 3, July 1977

IR-4 "Underground Lifelines in a Seismic Environment-Summary and Methodology", by P. Weidlinger, Weidlinger Associates, Grant P76-9838, Interim Grant Report No. 4, July 1977

CU-1 "Underground Pipe Damages and Ground Characteristics", by M. Shinozuka and H. Kawakami, Columbia University, Grant P76-9838, Interim Grant Report No. CU-1, June 1977

CU-2 "Free Field Strains and Ground Characteristics", by M. Shinozuka and H. Kawakami, Columbia University, Grant P76-9838, Interim Grant Report No. CU-2, July 1977

RESEARCH MEMORANDA

RM-1 "Dynamic Pipe-Soil Interaction Analysis - Finite Element Models", by J.M. McCormick and M.L. Baron, Grant P76-9838, August 1977.

RM-2 "Dynamic Pipe-Soil Interaction Analysis - Discrete Models", by J.P. Wright and S. Takada, Grant P76-9838, August 1977.

RM-3 "A Preliminary Study of Structural Network Effects in a Buried Pipe Network Subjected to Static Loading", by J. Isenberg, Grant P76-9838, June 1977

RM-4 "Free Field Earthquake Motions and Their Application to Buried Pipelines", by J.P. Wright and M.L. Baron, Grant P76-9838, (No date of issue as yet).

RM-5 "Some Aspects of the New Japanese Design Code, (Preliminary) for Petroleum Pipeline Systems", translated by T. Yoshizawa, Weidlinger Associates, Grant P76-9838, August 1977