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SOCIO-ECONOMIC ASPECTS AND STUDIES OF SPECIFIC EARTHQUAKES

PROGRESS REPORTS

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REPORT ON THE ACTIVITIES OF EARTHQUAKE ENGINEERING RESEARCH CENTER UNIVERSITY OF CALIFORNIA, BERKELEY

by Joseph Penzien[I]

I. SUMMARY

Presented is an overview of the activities of the Earthquake Engineering Research Center (EERC), University of California, Berkeley. Section II provides background information on the Center, Section III lists the available research facilities, Section IV summarizes the current research programs under the classifications, Structural Engineering, Geotechnical Engineering, Hydraulic Engineering, Engineering Seismology, Interdisciplinary, and International Cooperation, Section V describes the National Information Service in Earthquake Engineering (NISEE) public service program containing three components, namely, computer program dissemination, abstract journal, and information exchange, Sections VI and VII provide information on the Center's publications and personnel, respectively, and Sections VIII and IX contain a closing statement and acknowledgments, respectively.

II. INTRODUCTION

The Earthquake Engineering Research Center, University of California, Berkeley, was established as an organized research unit on November 30, 1967, to coordinate earthquake engineering research within the College of Engineering on the Berkeley campus. Its research and public service programs, which have as their ultimate goal the mitigation of the earthquake hazard, may be classified according to their objectives as follows: (1) determining the characteristics and intensities of strong ground motions, (2) developing mathematical models and analytical procedures for estimating potential damage effects, (3) improving design methods and code requirements, and (4) collecting and disseminating information on earthquake engineering.

In the past, the activities of EERC have concentrated primarily on the technical fields with greatest effort involving researchers in various disciplines of civil engineering, i.e., structural engineering and structural mechanics, soil mechanics, foundation engineering, and fluid mechanics. Recently, the activities have expanded into other technical areas requiring interdisciplinary efforts of researchers in materials, civil engineering, electrical engineering, operations research, and engineering seismology. Future expansion is expected to include the development of activities in the general area of public policy which is important to the implementation of technical research results into engineering practice. This expansion will require the coordinated effort of researchers in economics, social science, political science, law, engineering, and engineering seismology. The overall trend in the expanding activities of EERC is consistent with

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the United States national effort and needs and is consistent with the broad interpretation of earthquake engineering research by the Division of Problem-Focused Research, Directorate of Engineering and Applied Science, National Science Foundation, which is the primary source of funding for earthquake engineering research in the United States.

III. RESEARCH FACILITIES

Excellent research facilities are available for conducting earthquake engineering research at the University of California, Berkeley.

The experimental facilities include the Earthquake Simulator Laboratory, the Structural Research Laboratory, and the Soil Mechanics Laboratory located at the University's Richmond Field Station, which is five miles from the Berkeley campus, and the structural research laboratories located in Davis Hall on campus. The central feature of the Earthquake Simulator Laboratory is a modern hydraulically-powered electronically-controlled bi-axial (vertical and horizontal) shaking table (20 x 20 ft.) capable of testing specimens weighing up to 120,000 lbs. under realistic seismic excitations of maximum credible intensity. This laboratory also has two portable 5000 lb. maximum force amplitude mechanical vibrators, each containing double rotating eccentric masses, which are used for dynamic testing of prototype structures. The Structural Research Laboratory provides a large tension (3,000,000 lbs.) - compression (4,000,000 lbs.) testing machine and a variety of fixtures capable of testing full-scale structural components and assemblages under force or displacement controlled quasi-static or dynamic loadings simulating realistic seismic conditions. Complementary testing fixtures of this same general type are also available in the Davis Hall laboratories. The Soil Mechanics Laboratory provides modern equipment for conducting experimental investigations on current seismic problems in the general area of soil mechanics and foundation engineering. Modern high speed data acquisition and processing systems are available in these laboratories.

To support the correlation studies of experimental results and the analytical research activities, the University provides modern computational facilities, including CDC-6400 and CDC-7600 computers. Also available to support the overall research program are extensive library facilities, including the Earthquake Engineering Library. This specialized library now has approximately 15,000 acquisitions providing access to current literature published throughout the world. It is an invaluable asset to the research activities of EERC.

IV. RESEARCH PROGRAMS

A. STRUCTURAL ENGINEERING

1. Shaking Table Tests

a. Three-story steel frame with diagonal bracing (R. W. Clough)* - A half-scale three-story steel frame structure was used to study the performance of diagonal bracing installed across the weak axis of a frame. Three types of bracings were studied experimentally: half inch tie rods with

* Name(s) in parenthesis indicate faculty participant(s) conducting investigation.

turnbuckles, 3/4 inch pipe sections welded at the end connections and central crossing, and double angle braces welded similarly. All tests have been completed and computer analyses have been correlated with the test results. Excellent correlation was achieved demonstrating the effectiveness of the mathematical models that were developed to represent the yielding and rupturing of the tie rods, and the yielding and buckling of the other bracing systems.

b. Three-story reinforced concrete frames (R. W. Clough) - A series of five two-story reinforced concrete frame structures have been tested. The first four specimens were tested with the horizontal excitation axis coinciding with a principal axis of the frame while the fifth specimen was tested with the horizontal excitation axis at 25° to the principal axis. This latter test was the first biaxial shaking table test of a concrete frame known to be carried out anywhere in the world. Correlation studies have been carried out between experimental results and analytical predictions of response. An objective of the investigation is the extrapolation of test behavior to expected field experience in real earthquakes.

c. Nine-story steel frame with uplift (R. W. Clough) - The uplifting behavior of building frames has been investigated using a one-third scale model of a nine-story, three-bay steel frame structure. In the most recent tests, the central bay of the structure was provided with K-bracings; thus, converting it effectively to a shear wall component. The tests were carried out to show how a shear wall frame behaves when subjected to seismic motions sufficient to cause uplift.

d. Single-story masonry houses (R. W. Clough) - Single-story masonry houses, consisting of typical wall panels assembled in a 16 ft. square with a typical timber truss roof structure bolted in place, have been tested to investigate their seismic performance and to develop improved design criteria.

e. Dam models (R. W. Clough) - As part of the University of California-National Taiwan University cooperative research program, shaking table tests have been conducted to investigate the seismic behavior of the Techi dam located in Taiwan. Experimental work has included development of a plaster-sand material with strength and stiffness properties adjusted for small-scale model similitude. Two types of models have been made with this material and tested on the shaking table: a segmented arch model to represent arch action of the prototype and a gravity section to represent the cantilever resistance of the prototype, each having a length scale factor 1:150. Three specimens of each type have been tested to failure. Analytical correlation studies are now being carried out.

f. Base isolation systems (J. M. Kelly) - Shaking table tests have been carried out to study the effectiveness of specially designed multi-layer natural rubber bearings in an isolation system designed to reduce seismic forces produced in building structures. The multi-layer design of the bearings provides a vertical stiffness several hundred times larger than the horizontal stiffness; thus, decoupling the building from the horizontal ground motion. A mechanical fuze in the form of a fracture sensitive shear pin is included in the system to provide restraint against wind loads. Theoretical correlation studies have been made in the investigation.

g. Equipment-structure interaction (J. M. Kelly) - A three-story steel frame, on which models of equipment are mounted, has been tested on the shaking table to study equipment-structure interaction effects during earthquakes.

Analyses have shown that light equipment having low damping can experience very large accelerations during earthquakes when mounted in large structures. The shaking table tests confirm the existance of these large accelerations under conditions which are often present in prototype structures. Design guidelines are being developed to cope with this problem.

h. Energy absorbing restrainers for nuclear power plant piping systems (W. G. Godden, J. M. Kelly) - Shaking table tests are being performed on small-size two-dimensional nuclear power plant piping systems using different types of support constraint. The main objective of the tests is to develop high energy absorbing support systems which will prevent large seismic forces from occurring in the pipes; thus, reducing construction and maintenance costs and providing enhanced safety. Correlation studies are being made using numerical analysis procedures and computer programs specifically developed for this purpose.

i. Oil storage tanks (R. W. Clough) - Over the past several years, a number of cylindrical tanks containing water have been tested on the shaking table to study both the sloshing and structural behavior of oil storage tanks during earthquakes. Both open and floating lid type tanks have been tested with both anchored and unanchored base conditions being used. Extensive analytical correlation studies have been conducted with the ultimate objective of developing improved design criteria for prototype tanks.

j. Frames and masonry walls (H.D. McNiven) - To provide basic response data for mathematical modelling using system identification procedures, a one-story steel frame and free-standing unreinforced masonry walls were tested on the shaking table using simulated seismic excitations. The steel frame was tested under a variety of conditions, i.e., with and without in-fill walls (masonry, prefabricated concrete, and timber). The masonry walls were constructed from minature bricks for appropriate scaling. Accelerations and displacement response time-histories were recorded for each test.

2. Component Tests

a. Masonry structures (H.D. McNiven) - Numerous tests have been performed on full-scale single masonry piers using a test fixture which provides realistic boundary conditions, develops full dead load conditions, and generates cyclic shear loads simulating seismic conditions. Specimen parameters which have been varied include: type of masonry construction, height-to-width ratio, amount and arrangement of steel reinforcement, and type of grouting. The influence of varying the sequence of loading on strength and stiffness has been investigated and repair procedures have been studied. A mathematical model has been developed for predicting the elastic behavior of masonry piers and for predicting the beginning of cracking. Plans are now being made to extend this investigation to shaking table tests which will allow an even better assessment of the validity of the mathematical model.

b. Concentrically braced steel frames (E. P. Popov, J. G. Bouwkamp) - Experimental and analytical work on three half-scale models of three-story steel frames with K-braces subjected to severe quasi-static loading has been completed. Good agreement between the experimental and calculated results can be obtained by proper modelling of brace behavior.

c. Steel struts and eccentrically braced steel frames (E. P. Popov) - Many large-size steel struts having several kinds of boundary conditions have been subjected to severe tension-compression cyclic conditions and a number of eccentrically braced frames for buildings have been tested under simulated seismic conditions. Improved methods of analyses are being developed to predict their behavior.

d. Tubular frames (E. P. Popov, S. Mahin) - Experimental studies have been performed on X-braced tubular steel frames of the type used in offshore construction. Two one-sixth scale models of a complete frame of a typical four-leg production platform designed for 100-ft. water depth according to current wind and earthquake conditions applicable to Southern California have been tested under simulated seismic conditions. The primary variable in these tests is the diameter to wall thickness ratio of the bracing struts. Ratios of 33 and 48 have been considered. Other structural details are representative of current design practice. In addition to being useful in assessing the inelastic cyclic behavior of tubular steel offshore structures subjected to severe earthquake excitations, the experimental results obtained in this investigation can be employed to evaluate analytical models for predicting the seismic response of such structures.

e. Reinforced concrete beam-column sub-assemblages (V. V. Bertero, E. P. Popov) - Large-size reinforced concrete (ordinary and lightweight) beam-column sub-assemblages have been tested under large deformation cyclic loadings simulating severe earthquake conditions. Some specimens have been complete with floor slab and a cross beam loaded with gravity forces. Associated tests designed to investigate bond deterioration have also been made. Mathematical modelling and analysis procedures are being developed for predicting the seismic behavior of reinforced concrete moment-resisting frames subjected to seismic forces.

f. Coupled and uncoupled reinforced concrete shear walls (V. V. Bertero, E. P. Popov) - An extensive test program is being conducted to determine the large-deformation cyclic performance of coupled and uncoupled reinforced concrete shear walls under simulated seismic conditions. Improved detailing and criteria for the steel reinforcement are being developed to insure good seismic performance. Mathematical models and dynamic analysis procedures are also being developed.

g. Infilled frames (V. V. Bertero, E. P. Popov) - The main objective of integrated experimental and analytical research is to develop practical methods for seismic-resistant design, as well as the repair and retrofitting of structural systems based on the use of moment-resisting frames combined with masonry or concrete infills. Several experiments have been conducted on one-third scale model specimens of the three first stories of an eleven-story, three-bay, ductile moment-resisting frame. While some of these specimens were tested as a basic frame, others were tested using different types of infills and reinforcement. A new strut model and a new modeling technique based on a constraint approach have been formulated for studying the behavior of infilled frames. Establishment of guidelines regarding the strength and deformation capacities required of infills when subjected to different types of earthquake excitations based on parametric analytical studies of complete infilled frame systems is in progress.

3. Field Tests (J. Bouwkamp, R. W. Clough, R. M. Stephen, E. L. Wilson)

Field tests have been conducted to obtain information on the dynamic characteristics of buildings of unusual design or construction and to compare the results obtained with analytical predictions of performance. Both ambient and forced vibration excitations have been used in these tests. Recently, a 42-story pedestal base building and two prefabricated buildings (one nine stories high, the other twelve stories) have been tested. Field tests have also been performed on a 40-ft. high water tank and the Techi arch dam in Taiwan.

4. Analytical Studies

a. Certain aspects of building response (A. K. Chopra) - Five different aspects of the seismic response of buildings have been studied: Coupled lateral-torsional response, soil-structure interaction effects, evaluation of simulated ground motions for building response predictions, effects of gravity loads and vertical ground motion, and effects of foundation tipping.

b. Three-dimensional inelastic structural response (G. H. Powell) - To date, inelastic seismic analyses of buildings have been almost exclusively two-dimensional even though realistic conditions impose three-dimensional inelastic behavior; thus, an effort is being made to extend dynamic analysis capability to three-dimensional nonlinear systems. Nonlinear structural elements have been developed for the ANSR (Analysis of Nonlinear Structural Response) computer program to allow three-dimensional modelling of beams and columns in buildings. A new version of ANSR (ANSR-II) has recently been released which expands its three-dimensional nonlinear analysis capability.

c. Behavior of large precast panel buildings (G. H. Powell) - Buildings made by stacking large precast panels are being used increasingly in seismic zones. Because they have structural characteristics which are different from conventional buildings, there is concern over their ability to withstand earthquakes. Because of this concern, an analysis procedure and computer program suitable for calculating the response of large panel buildings has been developed. The procedure models the structure as an assemblage of elastic panels connected by elastic joints. Several different joint models have been considered and parameter studies are being carried out.

d. Behavior of reinforced concrete joints (G. H. Powell) - Because experimental studies are so expensive, accurate analysis procedures are needed to predict the behavior of reinforced concrete joints under severe seismic loads. The major difficulty in developing an analytical procedure is that concrete is an extremely complex material, especially under cyclic loading. A sophisticated mathematical model developed by Bazant is being implemented into the ANSR-II computer program to handle this joint problem. While it is complex and expensive to use, it has the potential to provide accurate predictions of joint behavior.

e. Pile foundation modelling (J. Penzien) - An important step in the dynamic analysis of pile-supported structures is to derive the dynamic stiffnesses of their pile foundations. A new method has recently been developed which involves the following four steps: (1) decomposition of the soil resistance function to pile movement obtained by numerical solution of a boundary value problem into the product of two orthogonal functions yielding frequency-dependent subgrade stiffnesses, (2) computation of the dynamic stiffnesses of a single pile using the subgrade stiffnesses described above and the pile's inertia and damping properties, (3) determination of the pile group interaction factor using the soil resistance functions at adjacent piles when one pile in the group is excited, and (4) computation of the dynamic stiffnesses of a pile group from the results of steps (2) and (3) above. An independent check on this method is now being carried out using a finite element near field and a continuum model for the far field.

f. System identification (H. D. McNiven) - Methods of system identification are being used to develop linear and nonlinear mathematical models of structural systems. These methods have been used to develop models for a single-story steel frame structure, a three-story steel frame structure, and reinforced concrete beams. The models obtained accurately reflect both global and local behavior of these systems under realistic seismic conditions. Much has been learned in these investigations regarding the effectiveness (or ineffectiveness) of various response data in developing mathematical models through the use of system identification procedures.

g. Response of highway bridges (J. Penzien) - Over the past several years, analytical procedures and computer programs have been developed for predicting the nonlinear seismic response of highway bridges. Presently, parameter studies are being carried out with the objective of improving seismic design criteria and the previously developed analysis procedures, and computer programs are being documented for better use by the practicing engineer.

h. Response of dams (A. K. Chopra) - The basic purpose of this investigation has been the development of techniques for earthquake analysis of concrete dams, including effects of hydrodynamic and foundation interaction, and the development of an understanding of these effects on seismic response. Gravity and arch dams have been included in the study.

i. Response of rigid blocks (A. K. Chopra, W. G. Godden, J. Penzien) - A numerical procedure and a computer program have been developed to solve the nonlinear equations of motion governing the rocking of rigid blocks on a rigid base subjected to horizontal and vertical earthquake ground motions. Results obtained by this procedure and by shaking table tests show the response to be very sensitive to small changes in block size and slenderness ratio and to details of the ground motion; thus, it is concluded that realistic estimates of ground motion intensity based on observed effects on monuments, minarets, tombstones, and other similar objects can be made only in probabilistic form and then only when suitable data in sufficient quantity are available.

j. Computer-actuator-on-line control for seismic testing(S. A. Mahin) - Numerical computer simulations are being performed to assess the reliability of a relatively new experimental method for testing structural systems that are too large, massive or strong to be tested on existing shaking tables. A computer is used on-line to monitor and control a test specimen so that quasi-statically imposed displacements closely resemble those that would be developed if the specimen were tested dynamically. Experimental information regarding the nonlinear force-deformation characteristics of the test specimen are used during the test by the computer, along with numerically prescribed information on the specimen's inertial and damping characteristics to determine the deformation that should be imposed for a numerical specified ground motion.

k. Post-earthquake damage analysis (V.V. Bertero, S.A. Mahin) - Various analytical and field investigations have been performed on structures damaged during recent major earthquakes. The objectives of these studies are (1) to identify the structural and/or construction causes of the observed damages, and thereby, assess the adequacy of current seismic resistant design, analysis, and construction methods, and (2) to suggest improvements in current seismic-resistant design practices. To accomplish those objectives, results of detailed analytical studies performed using elastic and inelastic dynamic analysis computer programs have been evaluated in terms of their ability to predict observed damages in selected buildings and in liquid storage tanks.

l. Safety evaluation of buildings exposed to earthquakes and other catastrophic environmental hazards (Bertero, Bresler, Axley) - Research efforts are devoted first, to refining both the methodology and the analytical models developed for evaluating structural response to normal and extreme environments; second, to applying the methodology and analytical models developed in a comprehensive analysis of an existing building; and third, to assessing the implications of the results obtained for practical application of the developed methodology by professional engineers, and suggesting practical guidelines for evaluating damageability of existing buildings by relatively simple means.

Damageability models for evaluating potential hazards to structures exposed to seismic or other extreme environments have been developed. In these models damage indices are associated with energy absorption capacity and with energy dissipation. The effects of two types of interaction between structural elements on damageability of the system are also investigated. A study of damage mechanisms in secondary structural elements (sometimes called nonstructural elements) has also been carried out. It focuses on panel-type elements, such as partitions, exterior finish panels, and windows.

m. Reliability analysis of structures (A. Der Kiureghian) - Probabilistic methods for reliability analysis and design of structures under multiple time varying loads have been developed with emphasis on the second-moment reliability technique. In addition, dynamic analyses of structures subjected to random earthquake type excitations have been carried out with special attention given to the responses of structures with closely spaced modes and to the response of tuned equipment in structures.

n. Development of automated seismic-resistant design procedures (V. V. Bertero, S. Mahin) - The main objective of this research is to develop automated seismic-design procedures that will satisfy three limit states simultaneously (serviceability, damageability, and safety against collapse). One such procedure has already been developed applying an optimization technique for the design of ductile reinforced concrete moment-resisting frame buildings. Reliability analyses of designs based on this procedure show significantly improved seismic response over standard designs based on present code provisions. A similar automated seismic-design procedure is being developed for reinforced concrete frame-coupled shear wall systems.

B. GEOTECHNICAL ENGINEERING

1. Evaluation of Liquefaction Potential (H.B. Seed)

A detailed investigation is being made of the influence of sample disturbance on the cyclic load characteristics of specimens tested in the laboratory. The investigation includes tests on soil specimens obtained by block-sampling, undisturbed tube sampling, freezing techniques and tube sampling with freezing, and comparison of the results with those of the in-situ material from which the samples were extracted.

In addition a field study has been made of the conditions producing soil liquefaction at La Playa on the shore of Lake Amatitlan during the 1976 Guatemala earthquake. Liquefaction was shown to occur in a lightweight pumiceous sand, but the investigations indicated that the field behavior was consistent with standard approaches for investigating the liquefaction potential of soil deposits.

2. Influence of Soil Conditions on Ground Responses (H.B. Seed)

A study has been made to determine the influence of soil conditions on ground response during earthquakes, taking advantage of new data concerning site conditions at recording stations which has only recently been made available. Spectra have been normalized both with respect to peak acceleration and peak velocity and used to determine the influence of soil conditions on spectral shape.

3. Seismic Stability of Earth Dams (H.B. Seed)

The objective of this research is to contribute to the better understanding of the cyclic behavior of dense, granular materials in relation to the seismic stability of dams. Very few or no published results are available on the dynamic behavior of saturated coarse granular materials in the range of confining pressures and densities encountered in high earth-fill and rock-fill dams. Obtaining meaningful results from the dynamic analysis procedures for embankment dams developed in recent years requires the incorporation of representative dynamic soil properties.

A comprehensive cyclic triaxial test program was conducted on a modelled rock-fill material with the intent of simulating as closely as possible the field loading conditions developed during an earthquake. A modelled gradation with 2-inch maximum particle size was used for the 12-inch diameter specimen tested. Necessary design modifications were incorporated in the test facilities to accommodate a wide range of test pressures.

High pressure cyclic triaxial test equipment was designed and built, and samples of a modelled rock-fill material (gravel) with 1/2-inch maximum particle size were cyclically tested in a 2.8-inch diameter specimens after keeping them under sustained pressure for 10 weeks. The objective of these tests was to simulate the effect of aging of the dam on its cyclic response. The test results showed very significant increases in cyclic resistance in a relatively short period of 2-1/2 months when compared to data for normally consolidated samples tested immediately after compaction.

These results are now being used in the evaluation of the seismic stability of gravel-fill dams. In conjunction with these studies, procedures are being developed to evaluate the seismic response of dams taking into account their three-dimensional configuration when they are constructed in V-shaped valleys.

4. Evaluation of Site Response Characteristics (J. Lysmer)

A study is being made to determine the seismic response of horizontally-layered sites to arbitrary seismic motions comprising different combinations of surface and body waves. The primary purpose of this project is to predict approximately the temporal and spatial variations of the seismic environments which may be expected at any given site and a computer program site has been developed for this purpose. The program is only applicable, however, for sites located at some distance from the earthquake source.

Studies conducted to date involve comparisons of the motions resulting from the propagation of Rayleigh waves and vertically propagating waves in different soil conditions. It is clear that Rayleigh wave motions generated in a layered system are completely different in characteristics from those generated in a half space and the layered system theory is therefore a necessary prerequisite to understanding the effects of Rayleigh waves at soil sites.

5. Soil-Structure Interaction Analyses (J. Lysmer and H.B.Seed)

An analytical procedure is currently being developed which will permit the evaluation of soil-structure interaction effects, for three-dimensional embedded structures, and for wave fields of any arbitrary composition.

6. Analysis of Pore-Pressure Dissipation Effects on Post-Earthquake Soil Behavior (H. B. Seed)

In a number of cases it has been noted that soil instability has developed some short time (several minutes to several hours) after the cessation of earthquake shaking. Studies are being made to investigate how the dissipation of pore pressures generated in the soils by earthquake shaking may be responsible for these post-earthquake failures.

7. Interaction Between Shear and Compression Waves (W. N. Houston)

A study is being made of the soil properties involved in the simultaneous propagation of shear and compression waves in soils. Studies are being made using two types of apparatus. The first involves the use of resonant column techniques specially designed to simultaneously excite samples in both the longitudinal (compression) and torsional (shear) directions. The second involves the use of a new apparatus designed to excite a hollow cylindrical specimen simultaneously in the compressive and shear modes at strain amplitudes and frequencies approximately those experienced during earthquakes.

The resonant column phase, for which some preliminary data has been generated, will provide valuable information about the low-strain ("linear-elastic") interaction between shear wave excitation and compression wave excitation in a cohesionless material. This interaction will be studied as it relates to strain amplitude, density of material, and confining pressure.

The second phase, for which test data has just started to become available, will provide information about the complex interaction of these types of wave excitations in the higher-strain, non-linear range. The apparatus has been designed to provide some overlap in the strain range used for the resonant column testing. The hollow cylinder apparatus will also be used to study this interaction as it relates to strain amplitude, density of material, and confining pressure.

8. Influence of Site Characteristics on the Damage During the October 1974 Lima Earthquake (H. B. Seed, P. Repetto and I. Arango)

On October 3, 1974, a strong earthquake caused a total of 70 deaths in Lima, Peru, and in several villages to the south of the capital city. Property damage was estimated to be over $200 million. Experience gained from previous earthquakes indicates that in the greater Lima area, the overall damage to buildings is slight except for several pockets of moderate to serious damage. However, the soil conditions in the areas of high damage intensity are now known.

The effect of local soil conditions on the damage pattern has been studied for a number of previous earthquakes throughout the world. The studies show that depth to rock or rock-like material, and the characteristics of the soils overlying it in many cases have had a strong influence on the observed damage to structures. This project will study the soil conditions in the heavy damage areas during the 1974 Lima earthquake, to compare them with those in the light damage areas and to determine if the site conditions could account for the major differences in earthquake damage and whether such differences might have been anticipated on the basis of previous studies of such effects. The overall project will consist of six major studies: (1) damage survey and preparation of damage distribution map of the greater Lima area, (2) survey of subsurface conditions of Lima area, (3) boring and further geophysical tests of selected tests of selected sites, (4) laboratory tests of subsurface materials, (5) development of subsurface profiles, and (6) analysis of data, soil response and cross comparison with results from previous earthquakes.

C. HYDRAULIC ENGINEERING

1. Analysis of Hydrodynamic Drag Forces on Offshore Structures (J. Penzien)

The dynamic analysis of offshore structures is made very complex by the fluid-structure interaction and the nonlinear form of the hydrodynamic drag forces. A special study has just been completed which compares the accuracy of results when drag is represented in three different ways: (a) in the original three-dimensional form represented by the well-known Morison equation, (b) in the so-called equivalent linearized form, and (c) in a modified nonlinear form suggested by Penzien and Tseng which is much more amenable to solution than using the nonlinear Morison form.

2. Hydrodynamic Forces on Submerged Structures (B.C. Gerwich, Jr., J. Penzien, R. L. Wiegel)

Analytical and experimental studies have been carried out to investigate the seismically induced hydrodynamic forces on underwater fixed structures. The experimental phase of the project has consisted of shaking table testing a submerged model of a storage tank and submerged vertical cylinders placed