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INNOVATIONS IN EARTHQUAKE AND NATURAL HAZARDS RESEARCH: DETERMINING SOIL LIQUEFACTION POTENTIAL

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November 1984

COSMOS CORPORATION 1730 K Street, N.W. • Suite 1302 • Washington, D.C. 20006

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Related Reports and Papers:

Moore, Gwendolyn B., and Robert K. Yin, Innovations in Earthquake and Natural Hazards Research: Local Government Liability, COSMOS Corporation, Washington, D.C., April 1983.

Moore, Gwendolyn B., and Robert K. Yin, Innovations in Earthqauke and Natural Hazards Research: Unreinforced Masonry Buildings, COSMOS Corporation, Washington, D.C., July 1983.

Moore, Gwendolyn B., and Robert K. Yin, Innovations in Earthquake and Natural Hazards Research: The Social Consequences of Earthquake Predictions, COSMOS Corporation, Washington, D.C., November 1983.

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PREFACE

The present case study is part of a project that is investigating the process by which innovations intended to reduce the effects of earthquakes and other natural hazards are utilized. The goal of the project is to improve the usefulness of these innovations to policymakers, state and local officials, service providers, and citizens.

The case study is about a research activity that produced the "dynamic analysis method." The method is used to assess the likelihood that soil liquefaction will occur--a phenomenon where soils literally change from a solid to a liquid state. The research was directed by Professor H. Bolton Seed at the University of California at Berkeley.

The case study is one of a series of nine--six will be widely disseminated, and three will be available to researchers upon request. In addition, a summary volume will discuss: the theoretical underpinnings of the project and its design and case selection procedures; the analyses across all nine cases; and specific policy recommendations--aimed at research investigators _and_ R&D funding agencies--to promote the utilization of future research.

Professor Seed was extremely helpful in conducting this case study. He gave generously of his time to describe the early stages of the research project, and comprehensively reviewed the draft of the case study; we would like to express our sincere appreciation to him for his help. We also wish to acknowledge the assistance provided by Claire B. Rubin, who helped the case study team to identify ways in which Seed's research has been utilized. Finally, we appreciate the continuing support and assistance of William A. Anderson, our NSF project officer. This assistance notwithstanding, the authors alone are responsible for errors or omissions.

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SUMMARY

The study of innovation can take many forms. One traditional dichotomy has been between knowledge production and knowledge use. The former includes such topics as creativity and invention, research and development (R&D) management, and commercialization processes; and the latter includes such topics as dissemination, diffusion, and utilization. Regardless of a study's focus, however, the objective is to improve society by understanding how new ideas are generated, produced, and used.

Innovations in Earthquake and Natural Hazards Research

The present case study focuses on knowledge use. The study analyzes how an innovation in earthquake and natural hazards research was used for practical and policy purposes, why utilization occurred, and what potential policy implications can be drawn. The case is the fifth of nine, all aimed at developing recommendations for improving research utilization in the future. (Six will be widely disseminated as final reports; three will be made available to researchers upon request.)

Research on earthquake and natural hazards offers a unique opportunity to study the utilization of innovations, because both social science and physical science innovations are relevant. For example, the first case in this series involved a social science innovation--the identification of local government liabilities in relation to losses due to earthquakes. This case study is of a physical science innovation--a method to assess the potential for soils to liquefy during earthquakes. Thus, the variety of innovations not only offers an opportunity to develop explanations for utilization, but also provides a chance to compare the utilization of social science and physical science innovations. Such a comparison has not, to our knowledge, been directly made in previous studies.

One of the tentative, overall findings from the first six cases and others now underway is that the traditional dichotomy between the

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knowledge production and knowledge utilization processes may have been misguided. Fruitful utilization seems to occur when the two processes are intertwined. For example, the second case was of a physical science innovation, involving a cost-effective process for evaluating and retrofitting unreinforced masonry buildings. In that case, significant utilization occurred even before the research project had been completed. Thus, future research and policy actions may have to account for such complex and nonlinear outcomes.

The Innovation

The innovation in the present case study was the "dynamic analysis method," used to identify those soils that are likely to liquefy during earthquakes. Liquefaction is a dramatic phenomenon, wherein soils instantaneously change from a solid to a liquid state. The research was initiated during an investigation into the cause of a liquefaction-induced landslide, at Turnagain Heights, in the 1964 Alaska earthquake. Other liquefaction-induced landslides have been responsible for extensive losses throughout history. The magnitude of losses associated with liquefaction made it important to develop knowledge about the conditions that would result in liquefaction, and the criteria for determining the likelihood of liquefaction occurring. Such knowledge could then be used in evaluating existing building sites, or in the siting or construction of such important new structures as dams, nuclear power plants, and high-rise buildings. If soils were found to be vulnerable, appropriate steps could be taken to reduce the likelihood of danger due to soil failure during earthquakes. The dynamic analysis method provided a way to conduct such analyses.

The research was designed and undertaken by H. Bolton Seed at the University of California at Berkeley. The research, conducted during the 1960's, included both the laboratory replication of liquefaction, and the development of tests to predict when liquefaction would occur. The research was a major breakthrough in engineering research, in that liquefaction had never before been reproduced in a laboratory. The laboratory work yielded quantitative information about the conditions under which liquefaction would occur. These data were then used to develop procedures for predicting liquefaction, that eventually eliminated the need for the laboratory testing of soil samples.

Uses of the Research and Explanations for Use

The dynamic analysis method has been used extensively by engineers throughout the world to evaluate the liquefaction potential of soils, and by decisionmakers in the development of codes relating to testing requirements for liquefaction potential. The case study discusses how the results of the project might have been used, and identifies specific ways in which the findings actually were used.

The utilization of the research results can be explained by examining a number of activities that occurred during the course of the project. These include: 1) the active participation of Seed in a network of both "academic" and practicing engineers; 2) the frequent interactions between Seed and potential users--e.g., practicing engineers and Army Corps of Engineer personnel--as the research was being conducted; 3) communications between Seed and potential users after the research was completed; and 4) the widespread dissemination of the results of the research.

Overall, the case study concludes that the interactions of Seed within a continuously active network of knowledge producers and users adequately explains the utilization of the dynamic analysis method.

Policy Implications

Although the case study presents the experiences of but a single innovation, the policy implications are discussed to establish a within-case rationale for the findings. Along these lines, future policies likely to favor utilization are those deriving both from a problem-solving and a social interaction perspective, in contrast to those deriving from a research, development, and diffusion perspective. Should this finding, which is consistent with that of the other case studies of this series,* be replicated in the subsequent case studies, the aggregate results will provide strong support for guiding individual research investigators as well as the R&D policies of such agencies as the National Science Foundation, the National Institutes of Health, and other federal and private research-funding organizations.

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*Four other cases, available for ordering, are listed on page ii.

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A METHOD FOR ANALYZING THE LIQUEFACTION POTENTIAL OF SATURATED SANDS

I. INTRODUCTION

Under certain stress conditions, such as occur during earthquakes, sandy soils will lose their cohesiveness and liquefy--like quicksand. Often, the liquefaction of soil during an earthquake is responsible for greater losses than the damage related to the failure of structures (e.g., buildings). For example, Figure 1 illustrates the results of liquefaction during the 1964 Niigata (Japan) earthquake, where large land areas liquefied and caused thousands of buildings to sink and tilt, even though the buildings themselves maintained their structural integrity (Ohsaki, 1966, reported in Seed and Idriss, 1982). Dam failures and landslides caused by liquefaction are equally disastrous. By one account, the entire city of Helice (Greece) was submerged and lost as a result of a liquefaction-induced landslide (Marinatos, 1960, reported in Seed, 1968).

An investigation into the cause of a major liquefaction-induced landslide during the 1964 Alaska earthquake--at Turnagain Heights near Anchorage--led a group of researchers to examine the specific conditions that had resulted in the landslide. These researchers, led by H. Bolton Seed of the University of California at Berkeley, subsequently developed a method for testing soils to determine their potential for liquefaction during earthquakes.

The purpose of the present case study is to document and explain the uses of this method, and to discuss the implications of these findings for future strategies to promote the utilization of earthquake and natural hazards research. (The individuals interviewed as part of this case study are listed in Appendix A.) The case study:

- discusses the problem of soil liquefaction, and the impetus for research on the topic;

Figure 1

FOUNDATION FAILURE AT NIIGATA, JAPAN

SOURCE: Seed, H. Bolton, and Kenneth L. Lee, "Liquefaction of Saturated Sands During Cyclic Loading," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, November 1966, p. 106.

- describes how the method was developed, and its contribution to engineering practice;
- outlines the uses to which the method has been put; and
- explains why utilization occurred.

This case study is one of nine. Each examines the utilization experience of a different earthquake or natural hazards research project. The findings relating to the soil liquefaction research are reported here; conclusions from all nine cases are reported in a summary volume.

The Problem of Soil Liquefaction

The liquefaction of soils during earthquakes has been responsible for extensive losses throughout history, including relatively recent earthquakes in Mexico in 1959, Chile in 1960, Alaska in 1964, and Niigata in 1964 (Peacock and Seed, 1968). As with other earthquake-related losses, the damage that occurs is a result of the interaction of the hazard with the man-made environment. Consequently, if liquefaction occurs in an uninhabited area, little damage will result; however, liquefaction-induced landslides can destroy acres of developed land in minutes. Further, when liquefaction occurs in soils that support building, bridge, roadway, and dam foundations, the structures are in jeopardy of sinking, shifting, and collapsing.

In the first two-thirds of the century, at least 30 major earthquake-induced liquefactions have occurred, causing untold millions of dollars in damage. Thus, the problem was to identify those circumstances under which liquefaction was likely to occur. If these circumstances could be identified, then man-made structures could be located to avoid potential dangers, or other remedial actions could be taken.

Impetus for the Research

The Turnagain Heights landslide involved an area of nearly 130 acres, that extended almost two miles along the Anchorage coast (Seed and Idriss, 1982, p. 15). This landslide focused immediate attention on the problem of soil liquefaction, and many months were spent to determine its cause. Initially, investigators had attributed the landslide to a loss of strength of clay. However, after six months of debate, scientists finally concluded that the cause of the landslide was the liquefaction of sandy soil. On the heels of this landslide was the Niigata earthquake, where liquefaction caused thousands of buildings to sink and tilt (refer to Figure 1).

As one researcher reported, there was an "instantly recognized need for a methodology to find out which soils were vulnerable to liquefaction and which were not."[1] At the same time, the federal government was showing an interest in the topic, especially because the Nuclear Regulatory Commission was in the process of planning and building several power plants, valued at billions of dollars, and posing potentially lethal dangers if threatened by soil failure during an earthquake.

The following section describes the research effort that led to a method for determining the liquefaction potential of sandy soils, and the contribution of this method to the practice of engineering.

NOTE TO SECTION I

[1]Interview with H. Bolton Seed, University of California at Berkeley, October 27, 1983.

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II. THE RESEARCH EFFORT

The research activities undertaken to develop a method for identifying the liquefaction potential of sandy soils began in mid-1964, during an investigation into the cause of the Turnagain Heights landslide. The research was initiated by H. Bolton Seed, of the University of California at Berkeley, and conducted with the assistance of two of his doctoral students.

Prior to 1964, none of the investigators had been directly involved in liquefaction research. However, Seed had conducted some related inquiries, and had investigated the response of soils to highway stresses and earthquake shaking (see, for example, Seed, 1960; Seed and Chan, 1960; Seed, Chan, and Lee, 1962; and Seed and Clough, 1962).

Prior Research on Liquefaction

It had long been recognized that soil conditions were directly related to the amount of damage observed following earthquakes (e.g., see MacMurdo, 1824; Wood, 1908; and Duke and Leeds, 1963). Also, the phenomenon of liquefaction--where soil instantaneously changes from a solid to a liquid state--had long been observed and understood qualitatively. For example, it had been observed that when saturated sand was subjected to ground motions, certain physical changes occurred within the sand. These changes were summarized by Seed and Lee (1966, pp. 105-106):

> If saturated sand is subjected to ground vibrations, it tends to compact and decrease in volume; if drainage is unable to occur, the tendency to decrease in volume results in an increase in pore-water pressure, and if the pore-water pressure builds to the point at which it is equal to the overburden pressure, the effective stress becomes zero, and the sand loses its strength completely, and it develops a liquefied state.

An early attempt was made by A. Casagrande (1936) to determine when liquefaction might occur under conditions of static stress (i.e., constantly applied pressure, as might result from the water pushing on a dam structure). Other investigators had studied the mechanisms by which liquefied sands moved, and a number of the specific factors believed to influence liquefaction were well known (e.g., the volume of soils, their ability to drain, and the ratio between the granules of the soil and liquids in the soils--see Seed and Lee, 1966, for a brief summary of previous research related to liquefaction).

This early research, however, had not identified the precise conditions under which soils would liquefy, especially when subjected to the cyclic stresses which accompany earthquakes (i.e., when pressure is exerted then relieved, exerted then relieved, etc.).

The magnitude of the Turnagain Heights landslide and the liquefaction-induced losses associated with the Niigata earthquake highlighted the importance of developing new knowledge about the conditions resulting in liquefaction, and the criteria for determining the likelihood of liquefaction during earthquakes. Thus, it was in recognition of this need for new knowledge, that Seed began to investigate the conditions that led to the liquefaction of sands.

Organizational Context

The research was conducted at the University of California at Berkeley, which has one of the world's largest departments of geotechnical engineering. Geotechnical engineering covers a number of courses of study, including soil mechanics, soil dynamics, foundation engineering, geological engineering, rock mechanics, and highway materials engineering ("Graduate Study and Research in Geotechnical Engineering," no date). Students engage in extensive research activities, as well as academic studies. Because of its California location, a great deal of the department's interest focused on topics relating to earthquakes.

Berkeley students also had ready access to the facilities of the Earthquake Engineering Research Institute, also located in Berkeley, which is a repository of earthquake-related resources and actively disseminates information on earthquakes and earthquake research.

The Research Effort and Results

Three individuals were the primary participants in the research effort:

- H. Bolton Seed,[1] who initiated and directed the entire research effort;
- Kenneth L. Lee,[2] a doctoral student, who worked to replicate liquefaction in the laboratory; and
- Izzat M. Idriss,[3] a doctoral student, who worked to develop analyses to predict when liquefaction was likely to occur.

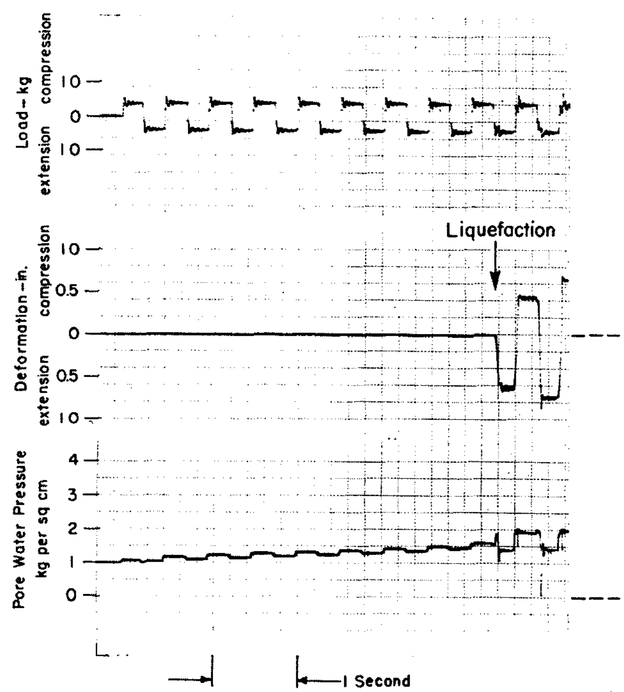
Both Lee and Idriss based their doctoral dissertations on their liquefaction work (see Lee, 1965; and Idriss, 1966). The research consisted of two primary elements: the laboratory replication of liquefaction, and the development of tests to predict when liquefaction would occur.

Laboratory Replication. Seed and Lee began trying to create liquefaction in the laboratory in early 1964. From field observations, they understood that soils were subjected to both vertical and horizontal stresses, which reversed directions many times, during an earthquake. The difficulty was in creating these conditions in the laboratory. This difficulty arose because the conventional shake table reproduced only vertical or horizontal shaking, but not both at the same time. The need to shake the soil in both directions simultaneously was a problem that was not easily surmounted and that stymied the research for a period of time. Subsequently, the clever insight of putting two shake tables on top of each other produced the multidirectional shaking needed, and the researchers suddenly recreated liquefaction in the laboratory in June of 1964 (see Seed and Lee, 1966, for a full description of their laboratory efforts).

Soil liquefaction is dramatic when reproduced, in that it occurs instantaneously when the threshold conditions are met. Figure 2, a record of a laboratory-induced liquefaction, demonstrates this. The first line shows the load (i.e., cyclic stress) being applied to a soil

Figure 2

LABORATORY RECORD OF LIQUEFACTION



SOURCE: Seed, H. Bolton, "Landslides During Earthquakes Due to Liquefaction," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, September 1968, p. 1059.

sample, and the third line indicates the change in pore-water pressure as the loads continue to be applied. At first, the middle line shows no deformation of the sample (note the straight line), but with the correct combination of cyclic loading and change in pore-water pressure, the sample liquefies instantly, as the immediate change in deformation line shows. Once the cyclic loading is stopped, the soil returns to its normal, solid state.

On the basis of their laboratory work, Seed and Lee reported that the likelihood of liquefaction was determined by the following conditions (Seed and Lee, 1966, p. 131):

1. The void ratio of the sand--the higher the void ratio, the more easily liquefaction will occur;

2. The confining pressure acting on the sand--the lower the confining pressure the more easily liquefaction will develop;

3. The magnitude of the cyclic stress or strain--the larger the stress or strain, the lower the number of cycles required to induce liquefaction; and

4. The number of stress cycles to which the sand is subjected.

Seed and Lee's work was a major breakthrough in engineering research, as liquefaction had never before been reproduced in a laboratory. For this advance, Seed and Lee were awarded the prestigious Norman Medal, in 1968, from the American Society of Civil Engineers (ASCE). The Norman Medal is the oldest of all awards administered by ASCE, and is granted for the paper, judged by ASCE, as "worthy of special commendation for its merit as a contribution to engineering science."

Having reproduced liquefaction in the laboratory, it was important to compare the laboratory-based predictions with known performance of soils in the field. Thus, analyses of the soil conditions in the Turnagain Heights landslide area were conducted (Seed and Wilson, 1967), and the soil conditions of previous liquefaction events from other areas were examined (e.g., Seed and Idriss, 1971). These analyses confirmed that laboratory tests, combined with analytical studies, could identify those soils that would or would not liquefy, under certain earthquake loading conditions.

Predictive Tests. The laboratory work had yielded quantitative information about the conditions under which liquefaction would occur. Using this information, Seed and Idriss began to develop testing procedures for predicting liquefaction that would not require the laboratory testing of soil samples, and would, at the same time, simplify the evaluation procedure. (One of the problems in relying on laboratory methods was that the act of removing the soil from the ground and moving it to the laboratory disturbed relevant characteristics, and threatened the reliability of the tests. This problem was later overcome by Seed, by developing a method of "freezing" the sand while it was being sampled and transported--e.g., see Singh, Seed, and Chan, 1982.)

Seed and Idriss (1971, p. 1252) reported a "simplified procedure" for evaluating liquefaction potential, involving the following steps:

1. Establish the soil conditions and the characteristics of any potential earthquake (i.e., the design earthquake);

2. Weight the various stress levels and stress cycles of the design earthquake, and plot the stress information as a function of depth;

3. Determine the cyclic shear stresses which would have to occur, at various depths, to cause liquefaction, using either available field data or laboratory soil tests; and

4. Compare the shear stresses induced by the earthquake with those required to cause liquefaction, to determine if an area exists within the soil deposit where liquefaction might be expected to occur.

Seed and Idriss also presented specific techniques for using this procedure to estimate liquefaction potential. This basic procedure has subsequently been refined (see Seed, Idriss, and Arango, 1983), but it remains as the core of current practice in testing for the liquefaction potential of sands. The primary difference in the procedure today and when it was first developed is that its accuracy precludes the need for confirming the results through laboratory test procedures.

Creation of the "Dynamic Analysis Method." Together, the laboratory replications and the predictive field tests allowed the Berkeley investigators to create a "dynamic analysis method," whereby soils in new locations could be tested for their liquefaction potential. Such testing could precede the siting or construction of such important structures as dams, nuclear power plants, and high-rise buildings, thereby reducing the likelihood of danger due to soil failure during earthquakes. The following section identifies how the method has been used, and discusses the extent of its use in engineering practice.

NOTES TO SECTION II

[1]Seed has remained at Berkeley, and is currently Professor of Civil Engineering.

[2]Lee was killed in a skiing accident in 1977.

[3]Idriss is currently a consulting engineering, with Woodward-Clyde Consultants, Santa Ana, California.

III. THE USES OF THE DYNAMIC ANALYSIS METHOD

The knowledge developed by the Berkeley reseachers on soil liquefaction is used as a standard tool by engineers throughout the world in evaluating the liquefaction potential of soils. This section identifies the potential uses of the research, discusses the widespread nature of the use, and contains examples of actual use.

Potential Uses and Users of the Research

Any assessment of the actual use of new research must begin with an analysis of the potential uses of such research. This is because some research may only have a limited potential, and if actual use fulfilled this limited potential, "broad" utilization could be said to have occurred. In contrast, the utilization of research with substantial potential but only limited actual use would be judged more critically. The potential uses of Seed's research--i.e., the dynamic analysis method--may therefore be analyzed as follows, considering that the research results can, theoretically, be employed for three major uses: enlightenment, decisionmaking, or practice.

Enlightenment use is a general recognition of, or orientation to, social science issues (Weiss, 1979). An enlightenment use could be said to "begin" when new knowledge raises awareness of certain issues, and be "completed" when new knowledge is codified (e.g., a common vocabulary emerges, or basic issues in an ongoing debate are recognized and defined). However, such enlightenment uses are quite difficult to disentangle from the effects of information available from other sources. In enlightenment, Seed's research could have served to sensitize decisionmakers, planners, engineers, and others regarding the soil liquefaction problem.

Decision-making use occurs when research helps to shape legislative initiatives, codes and regulations, or program activities. Such use can be readily observed--e.g., legislation is introduced, considered, and passed; a program is proposed, funded, and implemented. Seed's research could have been used as the basis for decisionmaking in at least two ways: 1) to develop regulations, ordinances, and statutes relating to analysis of the liquefiability of soils; and 2) to develop standards for guiding the analysis of the potential liquefiability of soils.

Practice use occurs when research influences changes in agency, organizational, or professional practice--e.g., the introduction and use of new technology, or the creation of professional certification requirements. This type of use can be observed in the actions of agencies and organizations. The dynamic analysis method could have been used in practice to evaluate soils, and, if liquefaction potential were found, to indicate ways in which the soil might be modified to resist liquefaction.

In sum, each of these three types of potential uses represents some change in how individuals think about or act with regard to a given issue--in this case, soil liquefaction. Of these, Seed's research was relevant to all three types of use. The full array of potential uses and users is summarized in Table 1.

Actual Pattern of Use

The primary use of the dynamic analysis method was in the practice of engineering, and such practice use was found to be substantial and extensive. Some evidence also indicates that the research findings were used for decision-making purposes. Finally, although no evidence was found, during the conduct of this case study, of the enlightenment use of the research, Seed was kind enough to point out a few examples of this type of use in his review of the draft case study. He also identified additional examples of other types of use as well.[1] Some of these examples have been incorporated into the text, even though the authors could not verify these events because of the limited time and resources available for the case study. (The reader is referred to Appendix B, which reproduces the letter from Seed containing these examples of the utilization of his research.)

Practice Use. The use of the dynamic analysis method is pervasive throughout the worldwide engineering community. Seven engineers, who

Table 1

POTENTIAL USES OF THE DYNAMIC ANALYSIS METHOD

TYPE OF USE	PRIMARY USERS
Enlightenment	
To increase awareness of the soil liquefaction problem or the ability to predict liquefaction	Elected Officials (e.g., delegates, representatives, senators) Federal Officials (e.g., executive branch personnel) State and Local Officials Code-writing Bodies Citizens
Decision-making	
To develop and adopt statutes requiring liquefaction analysis	Elected, State and Local Officials
To develop standards guiding site analysis and preparation	Code-writing Bodies
Practice	
To evaluate and test liquefaction potential of soils for new and existing structures	Engineers
To modify the composition of soils to reduce liquefaction potential	Engineers

were interviewed about the use of the dynamic analysis method, reported, collectively, the design of at least 145 structures in which they had used the method. These engineers also identified the dynamic analysis method as the primary method used for evaluating liquefaction potential. As one of the engineers commented, "Everyone who works in this area is using a method directly attributed to Seed or influenced by what he did."[2] Seed himself estimates that the method has been used in connection with "structures valued at over 100 billion dollars and affecting the safety of millions of people."[3]

In addition, a number of illustrative examples of the international application of the method were identified: the method was used in Argentina to evaluate the Alicura power project (Paitovi, PiBotta, and Longobardi, 1982), in Kuwait for an undersea pipeline, in Peru for concrete irrigation dams, and for pipeline construction in Greece (also see Vignette No. 1).

Vignette No. 1: Refinery Tank Farm[4]

In a consulting assignment for an oil company in Tokyo, Professor Robert Whitman used the dynamic analysis method to analyze the foundation conditions at an existing oil refinery and tank farm. The tank farm which contained about sixteen 500,000-kiloliter tanks of oil, was built about 1968 on a hydraulic fill site.

About four years ago, the oil company owners realized the need to analyze the foundation conditions of the structures. They were concerned about their potential losses, and also liability, if one or more of the tanks were to fail. There had been a number of tank failures in Japan in recent years, some due to earthquakes. One failed oil tank had seriously polluted a harbor area, resulting in significant cleanup expenses to the owner.

Whitman was asked to assess the foundation conditions, given the known seismic and other hazards in the area. Among the considerations was the need for the structures to withstand an earthquake comparable to the one that occurred in the area in 1923. Whitman's analysis revealed potential liquefaction problems. Based on the analysis, the company began a significant site improvement effort, at a cost of about $1 million. The improvements included de-watering the site and constructing a slurry wall around the site.

In the United States, the dynamic analysis method has been used extensively to evaluate dams, nuclear power plant sites, and other major structures. The diversity of this practice use is reflected in the following three vignettes.

Vignette No. 2: Federal Dams[5]

The near failure of the San Fernando Dam during the 1971 earthquake served as the impetus for the Army Corps of Engineers to evaluate several federal dams that were hydraulic fill-type dams. One of these was the Fort Peck Dam in Montana. The Corps assigned several persons to examine what might happen to the dam if an earthquake were to occur in the area. The study cost approximately $350,000 and took several years to complete. In the study, the Corps used the dynamic analysis method to analyze the dam, and concluded that the dam was safe from liquefaction (Marcuson, Krinitzsky, and Kovanic, 1977).

As knowledge of both dam safety and seismic hazards has increased, the Corps has been re-evaluating many federal dams throughout the U.S.--e.g., one on Jackson Lake, Wyoming, and another one near Charleston, South Carolina. By using the dynamic analysis method, the Corps tries to anticipate problems and take corrective or protective steps to ensure dam safety in areas of seismic risk.

Vignette No. 3: Municipal Dams[6]

Immediately after the 1971 San Fernando Earthquake, there was serious concern among engineers and scientists about other hydraulic fill dams. The State of California enacted a requirement that all dams over a certain size be evaluated to ensure their safety. The East Bay Municipal Utility District owned four dams that required evaluation.

The Upper San Leandro Dam was to be evaluated first. Woodward-Clyde Consultants, a consulting engineering firm, was engaged to evaluate the dam. In analyzing the dam, the firm used the dynamic analysis method developed by Seed. Seed also served as a consultant to the District, and aided in the analysis of the results. The results indicated that there was potential danger of liquefaction with the San Leandro Dam. Consequently, the District built a new embankment dam immediately downstream from the existing dam.

The same engineering firm and the same analytic steps were followed for a second dam, the San Pablo Dam. It, too, was found to be unsafe due to liquefaction potential. The District provided buttress fill on the up-stream side of the existing San Pablo Dam, to enhance its safety. The cost of these two evaluations, and the subsequent construction to enhance the safety of the dams, was approximately $30 million.

Vignette No. 4: Sewage Treatment Plant[7]

Because of the seismic activity in many parts of California, a foundation investigation is usually performed prior to the construction of any major project. In that process, the soil liquefaction potential is analyzed. About five years ago (1978-79), in preparing to construct a sewage treatment plant in Santa Barbara, a foundation investigation was done, using the dynamic analysis method. The analysts found loose sand material on the proposed site, which they determined was likely to liquefy under the known earthquake conditions in the area. Their solution was to make "stone columns," which is done by drilling holes and filling them with gravel, to strengthen the foundation.

Shortly after the sewage treatment plant was constructed, a small but significant earthquake struck the area. The earthquake provided a real test of the plant, which held up well. Some settlement did occur, but the engineers had anticipated that might happen.

Decision-Making Use. Two specific examples of decision-making use were found. The first is the California requirement that dams over a certain size be evaluated for their liquefaction potential. A second example is Section 720.4 of the Massachusetts State Building Code, which sets forth procedures for evaluating the liquefaction potential of soils. The drafters of this Section of the code were "heavily influenced"[8] by the research Seed had conducted on soil liquefaction, and established procedures essentially the same as those Seed had developed. In addition to these examples, Seed also noted other decision-making uses, including those by: the Building Code in China, the Tentative Provisions developed for a new U.S. National Building Code for Earthquake-Resistant Design, and the nuclear regulatory authorities in the United Kingdom, South Africa, and Italy (see Appendix B).

Enlightenment Use. (These uses draw largely on examples cited by Seed--see Appendix B.) The topic of soil liquefaction, or the ability to conduct tests for liquefaction, has not become a widely-known one because the potential audience--e.g., soils engineers or persons living in earthquake-prone areas--is rather limited. Nevertheless, information about liquefaction has appeared in some "popular" forms, such as the article "When Soils Start to Flow," which appeared in Mosaic; an exhibit at the British Museum two years ago on liquefaction; a controversy about the possible damage from liquefaction to the California School for the Blind and Deaf; and the establishment of a local committee, in San Bernadino, California, to assess the severity of the liquefaction problem.

In addition, all of the engineers who were contacted in connection with the present study were fully aware of the liquefaction research that Seed had conducted. This serves as evidence of enlightenment within the user community.

Summary. Of the potential use of Seed's research for practice, decisionmaking, and enlightenment, all of these potential uses were found during the present case study. For practice, the use was found to be extensive. Some evidence of the use of the research for decisionmaking also was found, as was evidence of enlightenment. The following section explains why these uses might have occurred.

NOTES TO SECTION III

[1]Seed has categorized several practice uses within the enlightenment and decision-making sections of his letter.

[2]Interview with John T. Christian, January 12, 1984.

[3]Letter from Seed to Gwendolyn B. Moore, dated July 2, 1984, p. 2.

[4]Interview with Professor Robert Whitman, January 17, 1984.

[5]Interview with William F. Marcuson, January 12, 1984.

[6]Interview with Dave Dayton, January 17, 1984.

[7]Interview with Robert T. Wong, January 20, 1984.

[8]Interview with Professor Robert Whitman, October 17, 1984.

IV. EXPLAINING UTILIZATION

One criterion for defining the utilization of a research project is when the "new knowledge, insights, and techniques that are produced [by it are] applied" (Glaser and Taylor, 1973, p. 140). A number of studies have been devoted to understanding the factors that influence the utilization of research results by three potential audiences or "users" (see, for example, Glaser and Taylor, 1973; White and Haas, 1975; Ball and Anderson, 1977; Weiss, 1980):

- Policymakers, at the federal, state, and local levels, who must make decisions about resource allocations, program support, or new legislation and regulations;
- Service providers, who are involved in the operation of actual services, e.g., emergency and disaster planning and relief activities; and
- Citizens, who may be the victims of earthquakes and other natural disasters.

Not included as potential users of natural hazards research are other researchers, who indeed also use research results, but whose utilization experiences do not raise the same public policy questions as used by the three preceding audiences.

The purpose of the present case study is to draw from the utilization experience with the dynamic analysis method, and to compare it with what is known about the utilization process, to develop specific, operational advice to promote the utilization of the results of natural hazards research by policymakers, service providers, and citizens.[1]

Models of Research Utilization

A number of explanatory models of the knowledge dissemination and utilization process have been developed--three by Havelock (1969) and four additional ones by Weiss (1979).[2] The seven models predict the presence or absence of different kinds and sequencing of events and interactions in the utilization process, and help to identify the activities that are likely to promote dissemination and utilization.

However, the models are, as a group, overly general. They provide too broad and diverse a perspective for specific operational action, should one desire to promote utilization in the future. Thus, the purpose of case studies such as the present one is to compare the models with actual experience, in the hope of discovering which models may be more critical and what specific actions might be considered in the future. In this sense, the models provide the opportunity for a "pattern-matching" effort (Campbell, 1975), where the preferred model becomes the one that is most consistent with the known facts of a situation. As an example of but one part of a pattern, for the problem-solver model to be supported, a practical or decisional problem must have been identified before the research was initiated; the model would not be applicable if the research had not addressed a problem specified before the research was started. Through this type of "matching" of circumstances between case experience and a theoretical model, consistent and operational explanations of utilization behavior can be generated.

The three Havelock models are:

- the problem-solver model;
- the research, development, and diffusion model; and
- the social interaction model.

The four Weiss models are:

- the political model;
- the tactical model;
- the enlightenment model; and
- the research as intellectual enterprise model.

For the present case study, the three Havelock models are relevant, and are discussed below. The Weiss models deal with situations inappropriate to the present case, and hence, are not discussed.[3]

The Problem-Solver Model. This model assumes that knowledge utilization is part of a user's problem-solving process, where the user specifies a problem and research is conducted to address it. The model is thus "user-oriented" and asserts that:

- The user's world is the only sensible place from which to begin to consider utilization;
- Knowledge utilization must include a diagnostic phase where user-need is considered and translated into a problem statement;
- Any external assistance [to the user] should primarily serve as a catalyst, collaborator, or consultant on how to plan change and bring about a solution;
- Internal knowledge retrieval [by the user] and the marshalling of internal resources should be given at least equal emphasis with external retrieval; and
- Self-initiation by the user or client system creates the best motivational climate for lasting change (Havelock, 1969, p. 11-13).

The crux of the problem-solver model as an explanation for utilization rests on a two-fold "pattern" of characteristics: 1) that research is initiated to address a previously-defined problem, and 2) that potential users are instrumental in defining the research problem.

The problem-solver model contributes partially to an understanding of the use of Seed's research. With regard to the first pattern of the problem-solver model, the research did address a previously defined problem: the need to understand the circumstances leading to soil liquefaction. Seed was aware of this problem when the research was begun, and the research was specifically aimed at it.

The second aspect of the problem-solver model, that of potential users defining the research problem, was not evident in this case. When Seed began working on the soil liquefaction question, it was in the capacity of a consultant to the firm of Shannon & Wilson, Inc., which was under contract to the Army Corps of Engineers. Although the Corps was aware of Seed's research on liquefaction, there is no evidence that the Corps--or other engineers--was involved in defining the research that was conducted.

The Research, Development, and Diffusion Model. The research, development, and diffusion model (RD&D) presents the utilization process as a linear sequence of activities. These activities are represented by a three-fold pattern of characteristics where: 1) the research to be performed is defined by the knowledge producer; 2) the idea being pursued moves from basic and applied research to development, packaging, and dissemination and utilization; and 3) the ultimate use of the research takes place in a commercial marketplace. Although this model is often considered in connection with the development and commercialization of "hardware" innovations (e.g., teflon-coated cookware), it is equally applicable to social science research where the "product" of the research can be, in Yin and Heinsohn's (1980) terms, "usable products"--e.g., instruments, handbooks, manuals, and other social science tools.

The RD&D model does not help to explain the utilization of Seed's research, as none of the patterns associated with the model were evident in the present case.

The Social Interaction Model. This model emphasizes communications between knowledge producers and users, especially through interpersonal networks, as a key to utilization. The user's networking characteristics should follow four basic principles:[4]

- The social network of the user is important and must be operative before utilization will succeed;
- Personal, one-to-one contacts within the network are important forces in facilitating utilization;
- The greater number and variety of "reference groups" a user has, the more likely the user is to be innovative and use new ideas;[5] and

- The user's position in that network will help to predict utilization behavior.

Beyond these principles, the crux of the social interaction model is a three-fold "pattern" of characteristics: 1) knowledge producers and users will belong to some overlapping network; 2) communication between them will occur while the research is in progress; and 3) communication will continue, or occur, after the research is completed.

The social interaction model contributes more than the other two models in explaining the utilization of the dynamic analysis method. Activities occurring during and after the research match each of the three patterns associated with this model. The first aspect, which suggests that utilization is likely to occur if the knowledge producer belongs to some overlapping network with potential users, is certainly true in the present case study. Seed was an active member of the American Society of Civil Engineers, the Berkeley Geotechnical Society, and the Earthquake Engineering Research Institute. Each of these organizations, and others to which Seed belonged, include in their membership both practicing engineers and university-based engineers. In the engineering field, in particular, knowledge users as well as knowledge producers belong to these professional organizations, thus providing each group ready access to the other. (In fact, in engineering the distinction between users and producers may not be as sharp as in other fields.)

In addition, a substantial amount of communication occurred between Seed and potential users while the research was in progress. He worked as a consultant to numerous engineering firms, thus providing a ready avenue for communication about his ongoing work. Seed reported that he gave approximately 20 talks and lectures to engineers during the course of a year, again providing an opportunity to discuss his research. In addition, the Army Corps of Engineers also was in contact with Seed during the early days of his research, and as soon as results could be used, they began to employ them in dam evaluations throughout the country (although as noted above, there is no evidence that the Corps influenced the direction of Seed's research). Finally, Seed began to publish the results of his research as soon as they were available (e.g., Seed and Lee, 1966).

The third aspect of the social interaction model, continuing communication between the producer and potential users after the research has been completed, also is quite evident. Seed and his colleagues were prolific writers, and published regularly in professional journals on the subject of soil liquefaction. Appendix C includes a list of nearly 60 publications, appearing between 1966 and 1983, that are directly related to Seed's initial research. (Numerous other publications, not directly related to liquefaction, are not included here.)

Seed was also quite active professionally, and was called upon frequently to present talks on soil liquefaction. He became a recognized expert on soil liquefaction, and was invited to present many prestigious lectures--including The Fourth Terzaghi Lecture in 1967, and The Rankine Lecture in 1979. In addition, Seed regularly co-publishes with practicing engineers. The practice of "academic" engineers and practicing engineers co-authoring articles appears to be a characteristic that is unique to engineering, and may help to explain the thorough utilization of the dynamic analysis method.

Summary. The nature and extent of utilization of Seed's research can be explained by comparing the pattern of events during and after the research with three models of the utilization process: the problem-solver model; the research, development, and diffusion model; and the social interaction model. Of the three models, the social interaction model almost completely explains the utilization of the results of Seed's research. The problem-solver model provides some additional understanding about the use of the research, and the RD&D model does not contribute at all.

Implications for Future Utilization Activities

The present case study covers just one set of experiences in which research was put to use. The purpose of the case study is not just to explain the utilization outcomes, but is also to discuss the implications for recommending future activities to promote R&D utilization.

Fifteen potential utilization-oriented activities have been identified[6] as opportunities for taking action to promote utilization. These activities have been further categorized to reflect their apparent role with regard to the problem-solver, RD&D, and social interaction models. Such a nonoverlapping scheme necessarily oversimplifies each activity, as some may be partially relevant to more than one model. Nevertheless, our desire was to examine the policy implications in this more simplistic manner, and there was sufficient match between the activities and the models to feel confident about the appropriateness of the basic scheme.

Table 2 presents the 15 activities, organized according to the three models, and indicates the actions that can be taken (either as part of the research project or by an R&D funding agency) to initiate each of the activities. The remainder of this section reviews the Seed experience as a way of suggesting which activities might be more preferred in the future. (The numbers in parentheses in the following paragraphs correspond to the number of the activity in Table 2.)

Activities Consonant with the Problem-Solver Model. Neither of the activities associated with the problem-solver model were evident during the course of Seed's research.

Activities Consonant with the RD&D Model. None of the six activities that are related to the RD&D model were evident in the course of Seed's research.

Activities Consonant with the Social Interaction Model. Two of the seven activities associated with the social interaction model were undertaken in connection with Seed's research. The first was the active dissemination of project results (11), through professional journals and the Berkeley College of Engineering's own paper series. The second was the provision in the Massachusetts State Building Code, and in other codes, regarding soil liquefaction (15).

Summary. This section has pointed to several specific activities, apparent in the present case study, that helped to promote utilization. Although only two of the actions were apparent in the present case study, the activities listed in the section provide illustrations of

Table 2

ACTIVITIES FOR PROMOTING THE UTILIZATION OF RESEARCH FINDINGS

Activity and Associated Model	Individual Research Project Action	R&D Funding Agency Action
Problem-Solver Model:		
1. User-oriented guidelines for new research.	Conduct some type of needs assessment at start of project.	Encourage and support R&D agenda conferences dominated by users.
2. Training sessions and workshops for users.	Initiate and conduct specific sessions during and after project.	Encourage and support specific sessions.
Research, Development, and Diffusion Model:		
3. Researcher-oriented guidelines for new research.	Review literature and consult other investigators at start of project.	Encourage and support R&D agenda conferences dominated by researchers.
4. Formal reviews and syntheses of previous research.	--	Support such research syntheses projects.
5. "Development" and applied research projects.	--	Support "development" and applied research projects.
6. Researcher training and and communication.	Enhance researcher training and professional development in project work.	Support researcher training and communication activities or programs.

Table 2, page 2

Activity and Associated Model	Individual Research Project Action	R&D Funding Agency Action
7. Commercial trade shows.	Participate in such shows at end of project.	Support trade shows.
8. Marketing and advertising of new products.	Do marketing and advertising.	--
Social Interaction Model:		
9. User advisory panel for individual research projects.	Use panel for life of project.	Require panel.
10. Research applications conferences.	Project staff should sponsor or attend conferences.	Encourage and support conferences.
11. Report dissemination.	Disseminate project reports.	Support computer-based clearinghouses and information services.
12. Special newsletters and journals about research findings and users' needs and experiences.	--	Support newsletters and journals.
13. Summer "institutes" for researcher-user interaction.	--	Support summer institutes.
14. Changes in practitioner certification requirements.	*	Support practitioner associations in reviewing certification requirements.
15. Changes in practitioner standards and codes.	*	Support practitioner associations in reviewing standards and codes.

*These two activities are mainly undertaken by professional associations.

how future policies might be designed to promote increased research utilization.

NOTES TO SECTION IV

[1]The present case study is one of a series of nine case studies, each examining the utilization experience of a different natural hazards research project. The findings from all nine cases are reported in the summary volume.

[2]Weiss actually specified seven models, but three correspond with the three Havelock models. Thus, those three Weiss models are not identified here. Each of these models is described in detail in the summary volume.

[3]The political and tactical models explain utilization as a function of political strategy or bureaucratic tactic, where the research is "used" to support a predetermined position or to fend off criticism. The enlightenment model deals with the use of a body of research ideas, often accumulated over a period of many years. Finally, the "research as intellectual enterprise" model de-emphasizes the importance of individual research efforts in favor of the pursuit of knowledge generally.

[4]Actually, Havelock specified six principles relative to the social interaction model. Two are not included here: one that deals with the adoption behavior of users, and the other that deals with how strategies to influence adoption decisions change with the five phases in the adoption process (awareness, interest, evaluation, trial, and adoption). Because adoption is but one portion of the utilization process, and because it deals with knowledge user rather than knowledge producer behavior, these two aspects of the social interaction model are not discussed relative to the utilization experience of Seed's research.

[5]A "reference group" represents, for the user, a set of individuals possessing attitudes and behaviors that the user perceives as normative.

[6]This list was compiled from two sources. First, some strategies were adapted from an article by Robert K. Yin and Margaret K. Gwaltney (Yin and Gwaltney, 1981). Second, a meeting was convened during the present case study of a number of government policymakers and others engaged in supporting or using natural hazards research. At that meeting, a number of strategies, based on the experience of those present, were added to the Yin and Gwaltney list.

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Marinatos, S. N., "Helice Submerged Town of Classical Greece," Archeology, Autumn 1960, 13(3).

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Appendix A

PERSONS INTERVIEWED FOR THE CASE STUDY*

John T. Christian, Stone & Webster, Boston, Mass.

Dave Dayton, East Bay Municipal Utility District, Oakland, Calif.

Ernesto R. Longobardi, Buenos Aires, Argentina (letter communication)

William F. Marcuson, III, U.S. Army Corps of Engineers, Vicksburg, Miss.

Phillippe Martin, HAZRA Engineering, Chicago, Ill.

H. Bolton Seed, University of California, Berkeley, Calif.

Gerald Thiers, International Engineers, San Francisco, Calif.

J. Lawrence Von Thun, U.S. Department of Interior, Denver, Colo.

Robert Whitman, Department of Civil Engineering, M.I.T., Cambridge, Mass.

Robert T. Wong, Geotechnical Consultants, Inc., San Francisco, Calif.

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*Affiliations shown are those at the time the interviews were conducted.

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July 2, 1984

Ms. Gwendolyn B. Moore
Project Director
Cosmos Corporation
1730 K Street, N.W., Suite 1302
Washington, D.C. 20006

Dear Ms. Moore:

I am sorry for the delay in responding to your letter of May 14. I have reviewed your draft of the case study of our research on soil liquefaction. As you requested I have marked up the draft to correct one or two main misconceptions concerning the technical details of the research and I am summarizing below my own assessment of the utilization of the research - where it is different from your own.

Personally I believe the research has been used extensively for enlightenment and decision-making purposes, in your terminology. Evidence for this is as follows:

Evidence of research being used for enlightenment purposes:

1. The enclosed copy of a general article taken from Mosaic magazine.

2. State and local officials are well aware of the liquefaction problem as evidenced by

   (a) The current concern about the problem in the city of San Bernadino, California where a local committee has been found to assess the severity of the problem for San Bernadino.
   (b) The mapping by the U.S. Geological Survey of liquefacable zones in the area of San Francisco Bay as a part of its San Francisco Bay study.
   (c) The presentation of a large exhibit on liquefaction, includes movies, at the British Museum two years ago.
   (d) The inclusion of liquefaction evaluations on the Seismic Safety Element reports required by the State of California for all cities and counties of the State.
   (e) The current controversy about the safety of the California School for the Blind and Deaf with regard to the safety of the new school location against liquefaction damage.

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Ms. Gwendolyn B. Moore
July 2, 1984
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Evidence of research being used for Decision making purposes:

1. It is used by regulatory agencies, in addition to code-writing bodies, to evaluate the work of engineering organizations:

   e.g. (a) The U.S. Nuclear Regulatory Commission
   (b) The State of California Division of Safety of Dams
   (c) The Building Code in China
   (d) The Tentative Provisions developed in the U.S. for a new National Building Code for Earthquake-Resistant Design
   (e) The Nuclear regulatory authorities in many other countries including United Kingdom, South Africa, Italy, Iran etc.

2. I would estimate that it has been used to regulate the foundation stability for at least 40 Nuclear Power Station in the USA and other countries and that involves the safety of constructed facilities valued at about 100 billion dollars.

3. It has been used by regulation agencies to make decisions concerning the public safety of major dam projects in many countries including some of the largest dam projects in the world, e.g. Tarbela Dam, Aswan Dam, Oroville Dam, etc.

4. It has been used to evaluate the public safety of LNG facilities and buildings all over the world.

In all of the above it has been used by Federal, State and local officials to make decisions concerning the safety of structures valued at over 100 billion dollars and affecting the safety of millions of people.

Finally I have a few more thoughts on why this research has been so widely used:

1. Because after developing the basic theory, which involved relatively sophisticated analyses and testing procedures, a continuing effort was made to progressively develop simplified approaches for liquefaction evaluations, based on experience with the use of the theory and field observations of the occurrence of liquefaction during actual earthquakes. Thus the procedure was progressively simplified and validated over a period of about 12 years.

2. Because the results were presented in clear and easy-to-understand papers and reports making it possible for all engineers to readily become familiar with the methodology - a good example being the monograph prepared by Seed and Idriss for publication by the Earthquake Engineering Research Institute.

Ms. Gwendolyn B. Moore
July 2, 1984
Page Three

I hope these ideas are helpful to you on finalizing your case study. Please do not hesitate to call me if you have any questions or if I can be of further assistance in any way.

Sincerely yours,

H. Bolton Seed

H. Bolton Seed
Professor of
Civil Engineering

HBS:edb

Enclosure

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Appendix C

LIST OF PUBLICATIONS RELATED TO THE SOIL LIQUEFACTION RESEARCH
(Listed in Chronological Order from 1966 to 1983)

1966

Seed, H. Bolton, "Soil Liquefaction in the Niigata Earthquake," Proceedings, Engineering Symposium, Tokyo, Japan, October 1966.

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1969

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