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INNOVATIONS IN EARTHQUAKE AND NATURAL HAZARDS RESEARCH: SYNTHETIC ACCELEROGRAMS

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December 1984

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This case study is part of a project 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 study examines a research project that developed synthetic accelerograms, computer-derived simulations of earthquake ground motions. The accelerograms serve as a tool for analyzing the design of important and complex structures (e.g., high-rise buildings and dams) to ascertain their likely response to earthquake shaking. 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.

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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 synthetic accelerograms. The accelerograms are an important analytic tool, used to design important structures (e.g., high-rise buildings and dams) to help to assure that they will withstand earthquake shaking. The research was conducted by Professors George W. Housner and Paul C. Jennings at the California Institute of Technology in Pasadena, California.

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 <u>and</u> R&D funding agencies--to promote the utilization of future research.

Professors Housner and Jennings were very helpful in conducting this case study, and we would like to thank them for the time they took to be interviewed and to review and provide useful comments on the draft of this case. We also wish to acknowledge the assistance provided by Claire B. Rubin, who helped the case study team to identify ways in which the synthetic accelerograms have 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.

G.B.M.
R.K.Y.

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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 sixth 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 in the earthquake and natural hazards field 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 tool for analyzing the design of a structure to ascertain its likely response 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 all nine cases is that the traditional dichotomy between the 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 study in this series 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 development of synthetic accelerograms. These are computer-derived simulations of earthquake ground motions. Important and complex structures--e.g., high-rise buildings, dams, nuclear power plants, and long-span bridges--in areas of earthquake risk must be designed to withstand the expected ground shaking. This design requires the use of recorded earthquake ground motions. Because the number and intensity of such recordings is limited, and often do not exhibit the properties relevant to the design project at hand, synthetic accelerograms filled an important need in the design community.

The accelerograms provided simulations of earthquakes representing a variety of duration, intensity, and frequency characteristics. Engineers were then able to identify the accelerogram that most nearly matched the special features of the design task at hand, and to use the acclerogram to analyze the response of a design structure under a variety of earthquake scenarios.

The research to develop the synthetic accelerograms was conducted between 1961 and 1968, by George W. Housner and Paul C. Jennings at the California Institute of Technology, Pasadena, California. The research included the development of a set of accelerograms and the articulation of the method used to generate them, thus permitting others to readily construct more specialized accelerograms to fit the special conditions of individual design projects.

Uses of the Research and Explanations for Use

The synthetic accelerograms have been used extensively over a 15-year period to analyze the designs of specific structures. The accelerograms have influenced the practice of engineers, the decision-making activities of public agencies, and the general "enlightenment" of individuals in the earthquake engineering community throughout the world. The case study discusses how the results of the project might have been used, and identifies specific ways in which the findings were actually 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 existence of a problem to which the research was addressed, and which fit into a stream of basic to applied research; 2) the frequent interactions between Housner and Jennings and potential users--e.g., practicing engineers--as the research was being conducted; and 3) communications between Housner and Jennings and potential users after the research was completed.

Overall, the case study concludes that the initiation of the research by the investigators to address an existing problem in the engineering field and the development of a tool that could be readily used to address that problem explains the utilization of the synthetic accelerograms. This was further augmented by the interactions of the investigators within an active community that included potential users of the research.

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 a research, development, and diffusion perspective and, to lesser extents, the problem-solving and social interaction perspectives. This mixture does contrast with that of the other case studies in this series,* and therefore will be discussed more fully in a cross-case analysis of all nine cases.** The aggregate results will provide 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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*Five other cases, available for ordering, are listed on page ii.

**The cross-case report is also available for ordering and it is listed on page ii.

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SYNTHETIC ACCELEROGRAMS FOR USE IN DESIGNING STRUCTURES: A RESEARCH ACTIVITY AT THE CALIFORNIA INSTITUTE OF TECHNOLOGY

I. INTRODUCTION

Buildings and other structures must be designed to withstand the normal stresses and strains to which they are expected to be subjected during their lifetimes. Most design in the United States is guided by the standards contained in the Uniform Building Code (1982). The Code establishes the minimum requirements for the construction of "ordinary" structures to withstand "normal" loads, and provides some earthquake design guidance as well. However, the Code does not provide sufficient guidance for the design of important and complex structures in earthquake zones, such as high-rise buildings, dams, nuclear power plants, and long-span bridges. For these structures, design professionals must turn to other resources.

One of these resources is a synthetic accelerogram, or simulated earthquake motion. Synthetic accelerograms are computer-derived simulations of earthquake ground motions at various intensities. In the design of complex structures, computer analyses are frequently made to project the likely response of the structure to a "prescribed base acceleration" (Jennings, Housner, and Tsai, 1968, p. 1).[1] Synthetic accelerograms are a very important element in these analyses, as the number and diversity of actual, recorded earthquake ground motions--the only other source of data--have been limited and have not exhibited the properties necessarily relevant to the design project at hand.

The present case study describes the research activities leading to the development of synthetic accelerograms, and explains how and why the accelerograms were ultimately used. (The individuals interviewed as part of this effort are listed in Appendix A.) The purpose of the case study is to add further to the development of policy recommendations for future strategies to promote the utilization of R&D.[2] Thus, the case study:

- Discusses the importance of synthetic accelerograms to the engineering design community;
- Describes the efforts taken to develop the accelerograms, and their contribution to engineering practice;
- Identifies several of the actual uses of the accelerograms; and
- Explains why such uses occurred.

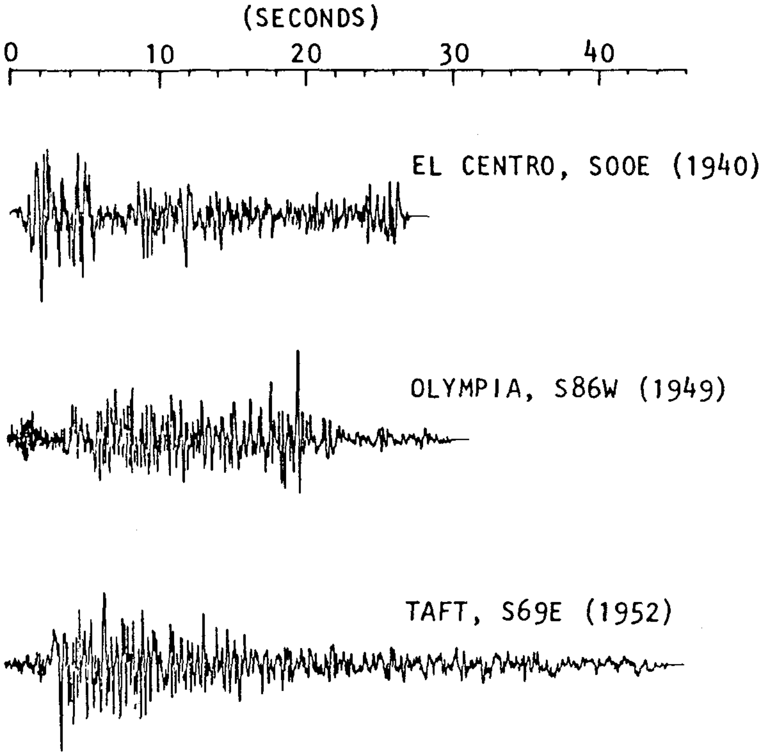
The Need for Synthetic Accelerograms

The predicted response of complex structures (e.g., high-rise buildings, nuclear power facilities, dams, or off-shore oil drilling platforms) to earthquake shaking is a critical factor in designing these structures. This response can be predicted by using computer analyses. For these analyses, mathematical models of structures are entered into a computer, and various "forces," also expressed mathematically, are "exerted" against the model structure.

To conduct these analyses, the data may come from actual, recorded earthquakes. However, the records of such earthquakes have been extremely limited, because of the "rarity of strong earthquakes, the localized extent of the really strong ground shaking, and the seeming proclivity of earthquakes to occur in uninstrumented areas" (Jennings, Housner, and Tsai, 1969, p. 1). For example, no recordings have been made, in the United States, of the very strong shaking of a Magnitude 8, or greater, earthquake. Although the records of actual earthquake ground motions that do exist have been used extensively for design purposes (e.g., the accelerograms of earthquakes in Taft, California, 1952; and El Centro, California, 1940--see Figure 1), their properties in fact have not necessarily been applicable to every given design project. Thus, a gap existed between the need of the engineering design community to use earthquake data, and the availability these data from recordings of actual earthquake motions.

Figure 1

ACCELEROGRAM OF THREE ACTUAL EARTHQUAKES



SOURCE: Housner, George W., and Paul C. Jennings, Earthquake Design Criteria, Earthquake Engineering Research Institute, Berkeley, Calif., 1982, p. 54.

The Impetus for Research to Develop Synthetic Accelerograms

A team of researchers at the California Institute of Technology (Caltech), who had been active in related aspects of earthquake engineering, recognized this need for synthetic accelerograms and perceived how they could be constructed. They knew that synthetic accelerograms could not only provide engineers with an important new tool, but that a range of accelerograms representing differences in the intensity, duration, and frequency content of ground motions could be developed. Further, because earthquake ground motions were known to exhibit certain statistical properties, the researchers also knew that synthetic accelerograms could be used with confidence, to design new structures to withstand earthquakes.

The first report on the simulated earthquakes (i.e., Jennings, Housner, and Tsai, 1968) contained accelerograms for earthquakes of Magnitude 8, 7, 6, and 5; and these have been used extensively in the design of complex structures. In turn, these structures, such as the first high-rise office building constructed in Los Angeles--the Union Bank Square Building--have transformed the skylines of major cities in earthquake-prone areas of the United States.

The techniques for constructing these first simulated earthquakes could be used to construct accelerograms for any magnitude of earthquake at any distance from the epicenter, and structural analysis now routinely employs accelerograms that have been prepared specifically to reflect the conditions of a given site or project. The engineering community credits the researchers who developed the first synthetic accelerograms with "pointing out the direction to go,"[3] and conducting "pioneering work for conceptualization"[4] of artificial accelerograms.

The following section of this case study describes the activities undertaken to actually develop the first synthetic accelerograms, and subsequent sections endeavor to explain the widespread use to which they were put.

NOTES TO SECTION I

[1] Base acceleration is the degree of shaking that a structure will experience, at its base, during an earthquake of specified intensity.

[2] This case study is one of nine, each examining the utilization experience of a different natural hazards research project. The findings relating to the synthetic accelerogram research are reported here; conclusions from all nine cases are reported in a summary volume.

[3] Telephone interview with Roger Scholl, Associate, John A. Blume Engineering, San Francisco; and Technical Director, Earthquake Engineering Research Institute, March 15, 1984.

[4] Telephone interview with Nilesh Chokshi, Structural Engineer, Structural Engineering Branch, Nuclear Regulatory Commission, March 23, 1984.

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II. THE RESEARCH EFFORT

Research Investigators

The research to develop synthetic accelerograms was conducted at Caltech during the 1960s. George W. Housner and Paul C. Jennings were principally responsible for the research, although N.C. Tsai also made an important contribution.

At the time the research was being conducted, Housner was Professor of Civil Engineering and Applied Mechanics at Caltech. Since 1974, he has served as the Carl F Braun Professor of Engineering. Jennings was a doctoral student during the early stages of the research; in fact, his doctoral thesis documented much of the research on synthetic accelerograms and its conclusions (Jennings, 1963). After a two-year hiatus at the U.S. Air Force Academy, Jennings returned to Caltech, where he is currently Professor of Civil Engineering and Applied Mechanics. Tsai, a graduate student, conducted much of the computer analysis needed to develop the synthetic accelerograms.

For many years prior to the research, Housner had published numerous articles on related aspects of earthquake ground motion and the response of structures to earthquake shaking (e.g., Housner and McCann, 1949; Housner, 1953b, 1955, and 1959; and Housner and Merritt, 1954). Jennings had done only limited previous research in the area (as one example, see Jennings, 1962).

Organizational Context

Caltech is an independent, privately supported university, with an enrollment of approximately 1,800 students (875 undergraduate and 900 graduate students), and the school has a large research staff of approximately 780 faculty members (for more information, see California Institute of Technology, 1983). Caltech is organized into six divisions: Biology; Chemistry and Chemical Engineering; Engineering and Applied Science; Geological and Planetary Sciences; the Humanities and Social Sciences; and Physics, Mathematics, and Astronomy. Research activities are stressed at Caltech, and students and faculty alike are strongly encouraged to pursue research goals.

Housner and Jennings were (and remain) in the Division of Engineering and Applied Science. The Division is large, and it accounts for almost one-half of Caltech's enrollment. The Division has had a series of general research grants from the National Science Foundation, which partially supported the development of the synthetic accelerograms.[1] As is often typical of research projects conducted in academic departments, the work conducted by Housner and Jennings was not an "isolated project, [it was] just the pursuit of general [research] interests."[2]

The Research Effort and Its Results

Prior Research Activities.

As previously noted, Housner had been active in the earthquake engineering field for many years. Housner recalls that he first thought of earthquake ground motions as random processes (see Housner, 1947), while serving in Europe during World War II where he "had a lot of time to think." Much of Housner's early work had focused on the analysis of strong-motion earthquake records and their general characteristics (e.g., see Alford, Housner, and Martel, 1953; and Housner and McCann, 1949), and on the actual testing and analysis of structures subjected to strong-ground motions (e.g., see Housner, Hudson, and Alford, 1953; Housner, 1953a; and Housner and Hudson, 1954).

Housner and others subsequently verified that the properties of strong-ground accelerations had well-defined statistical properties (e.g., Housner, 1959). Other investigators had modeled earthquake accelerograms by white noise (e.g., Hudson, 1956; and Bycroft, 1960). Although several different methods had been used to model earthquake ground motions, some practical limits were set by the lack of adequate digital computing equipment. (See Housner and Jennings, 1964, for a brief summary of prior research on modeling earthquakes.)

The Importance of Digital Computers.

In the early 1960s, digital computers were just beginning to appear in research laboratories around the country. Housner and Jennings appreciated that the development and use of the synthetic accelerograms would depend on the capabilities of such computers, and in one of their first published papers (Housner and Jennings, 1964), they explicitly noted that "the work...has as its objective the development of such an automated process" (p. 115).

One important related breakthrough, which allowed for the continuing development of artificial accelerograms, was the suitable generation of random numbers by the digital computer. J.N. Franklin of Caltech (1963a and 1963b) developed the procedure for generating an appropriate series of random numbers, using the IBM 7090 digital computer at the Caltech Computing Center.

During the early stages of the accelerogram research--around 1963--the practical utility of the accelerograms was limited because the engineering community generally lacked the required computer facilities. However, by the late 1960s when the work was completed, computers were more routinely available, so that the accelerograms could not only be developed, but could also be put to use in testing the designs of new structures.

The Development of Synthetic Accelerograms. The progression of the Caltech research can be followed by reviewing the major publications emanating from the research team:

1963: Response of Simple Yielding Structures to Earthquake Excitation, thesis at Caltech by Jennings;

1964: "Generation of Artificial Earthquakes," article in Journal of the Engineering Mechanics Division, ASCE, by Housner and Jennings; and

1968: Simulated Earthquake Motions, report of the Earthquake Engineering Laboratory at Caltech by Jennings, Housner, and Tsai.

Jennings (1963) originally presented a "derivation of a simple statistical model of strong-motion earthquake accelerograms...and an ensemble of samples of this model on the digital computer" (p. 12). He modeled earthquakes as a stationary, Gaussian, random process. Eight

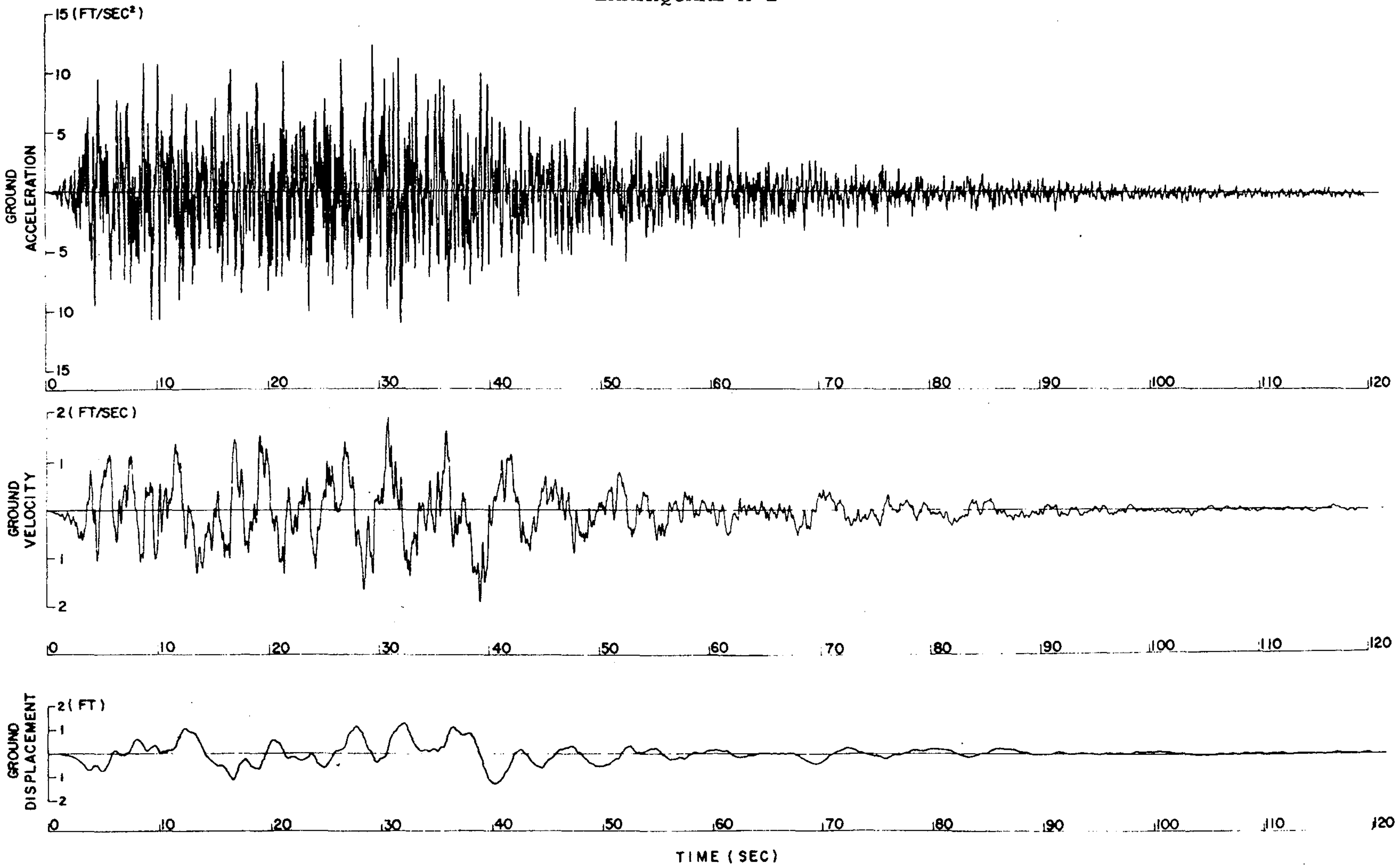
30-second sections of a random process were generated from a digital computer (the 30-second intervals were chosen because that time was estimated to be the duration of strong motion from a Richter Magnitude 8 earthquake). Thus, the models were to represent the strongest possible ground shaking associated with a major earthquake. The models were compared to the characteristics of real earthquakes, and were taken to "possess, individually and on average, the known properties of strong-motion earthquake records" (p. 14).

Housner and Jennings (1964) subsequently published the results of Jennings' thesis (Jennings, 1963), without making any substantive changes in the models or their assumptions about them. However, a significant change in the models was later presented in a 1968 report (Jennings, Housner, and Tsai, 1968). That report "contained a set of simulated accelerograms which could be used directly by design professionals but, more important, the report contained a description of how the simulation was done, so that it was a simple matter to construct more specialized accelerograms to fit special conditions of a project."[3] The report contained accelerograms that were modeled to represent a variety of ground shaking, "from a great earthquake, such as occurred in...Alaska in 1964, to a small, close shock as recorded in Parkfield, California in 1966" (Jennings, Housner, and Tsai, 1968, p. 4). (Recall that the accelerograms previously published--i.e., Jennings, 1963; and Housner and Jennings, 1964--had only modeled very strong shaking.) Specifically, two each of four types of accelerograms, representing earthquakes of differing Richter Magnitudes, were presented, as follows:

> TYPE A modeled a great earthquake of Magnitude 8 or greater (see Figure 2);
>
> TYPE B represented the strong shaking of a Magnitude 7 or greater earthquake (see Figure 3);
>
> TYPE C represented the shaking of a Magnitude 5.5 to 6 earthquake (see Figure 4); and

Figure 2

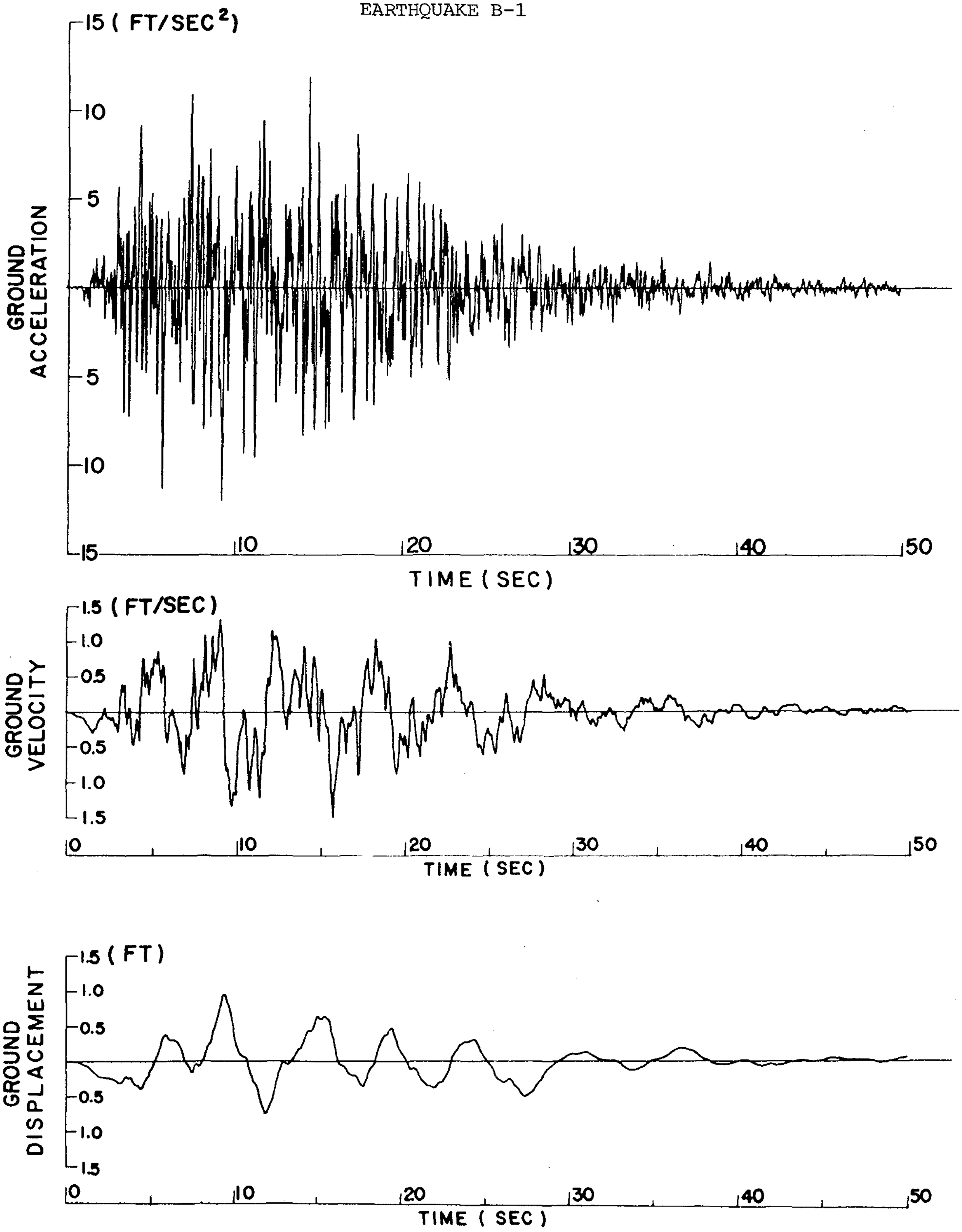
EARTHQUAKE A-1



SOURCE: Jennings, P.C., G.W. Housner, and N.C. Tsai, "Simulated Earthquake Motions," California Institute of Technology, Pasadena, Calif., April 1968.

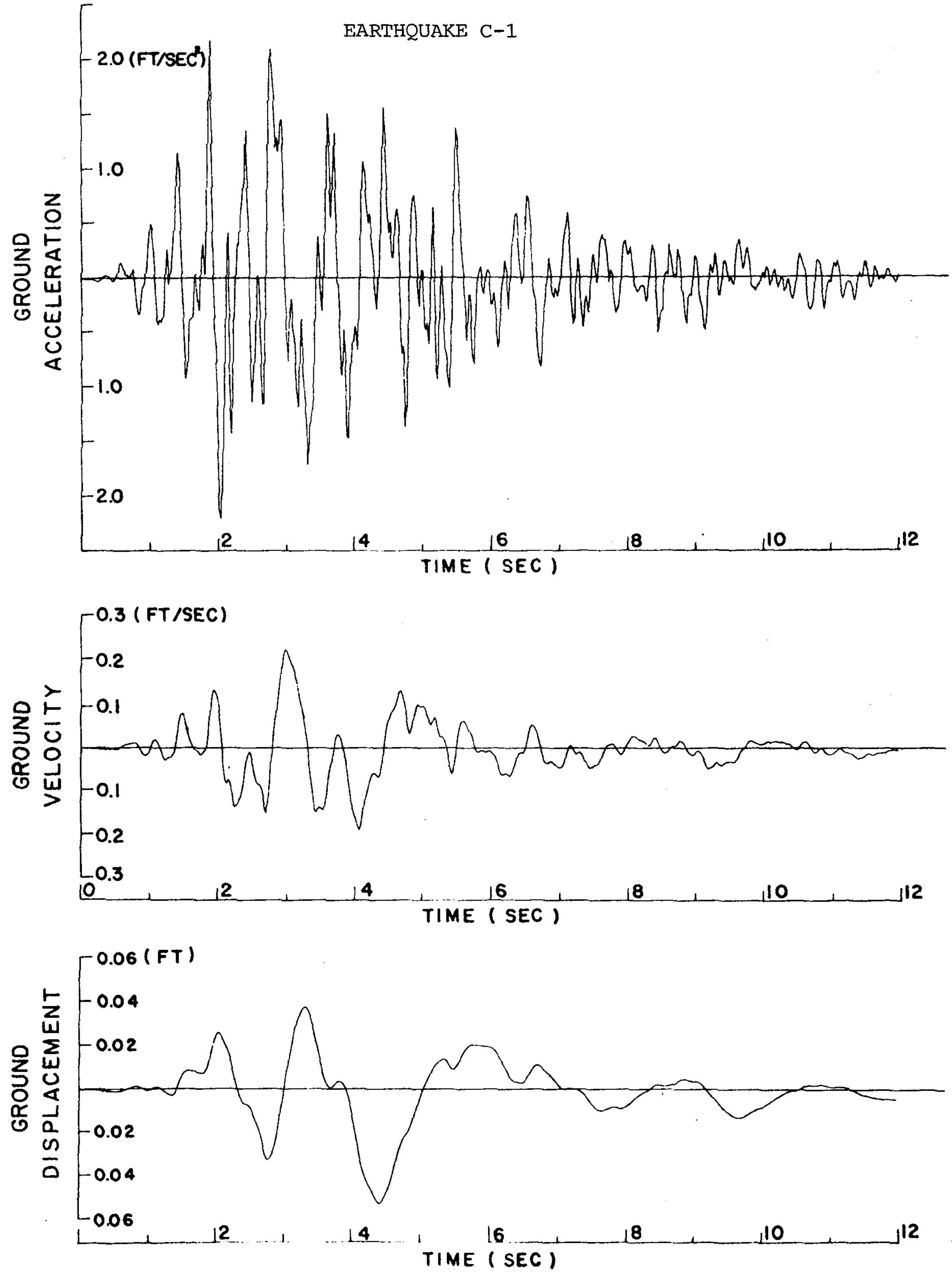
Figure 3

EARTHQUAKE B-1



SOURCE: Jennings, P.C., G.W. Housner, and N.C. Tsai, "Simulated Earthquake Motions," California Institute of Technology, Pasadena, Calif., April 1968.

Figure 4



SOURCE: Jennings, P.C., G.W. Housner, and N.C. Tsai, "Simulated Earthquake Motions," California Institute of Technology, Pasadena, Calif., April 1968.

TYPE D modeled the shaking of a shallow, Magnitude 4.5 to 5.5 earthquake (see Figure 5).

The eight models differed from the ones originally depicted (Housner and Jennings, 1964), in that they now represented smaller earthquake motions and the less intense "tails" of accelerograms.[4] (The original accelerograms had only represented the strong-motion portion of earthquake shaking.) To convert the accelerograms, the original models were multiplied by "envelope functions" of the nonstationary processes of accelerograms (recall that the original accelerograms were based on a stationary process). A summary of the actual process of developing the accelerograms is presented as Appendix B.

In addition to the published results of the accelerogram research, copies or listings of the accelerogram card decks were made available to interested parties on request.

Contribution to Engineering Practice

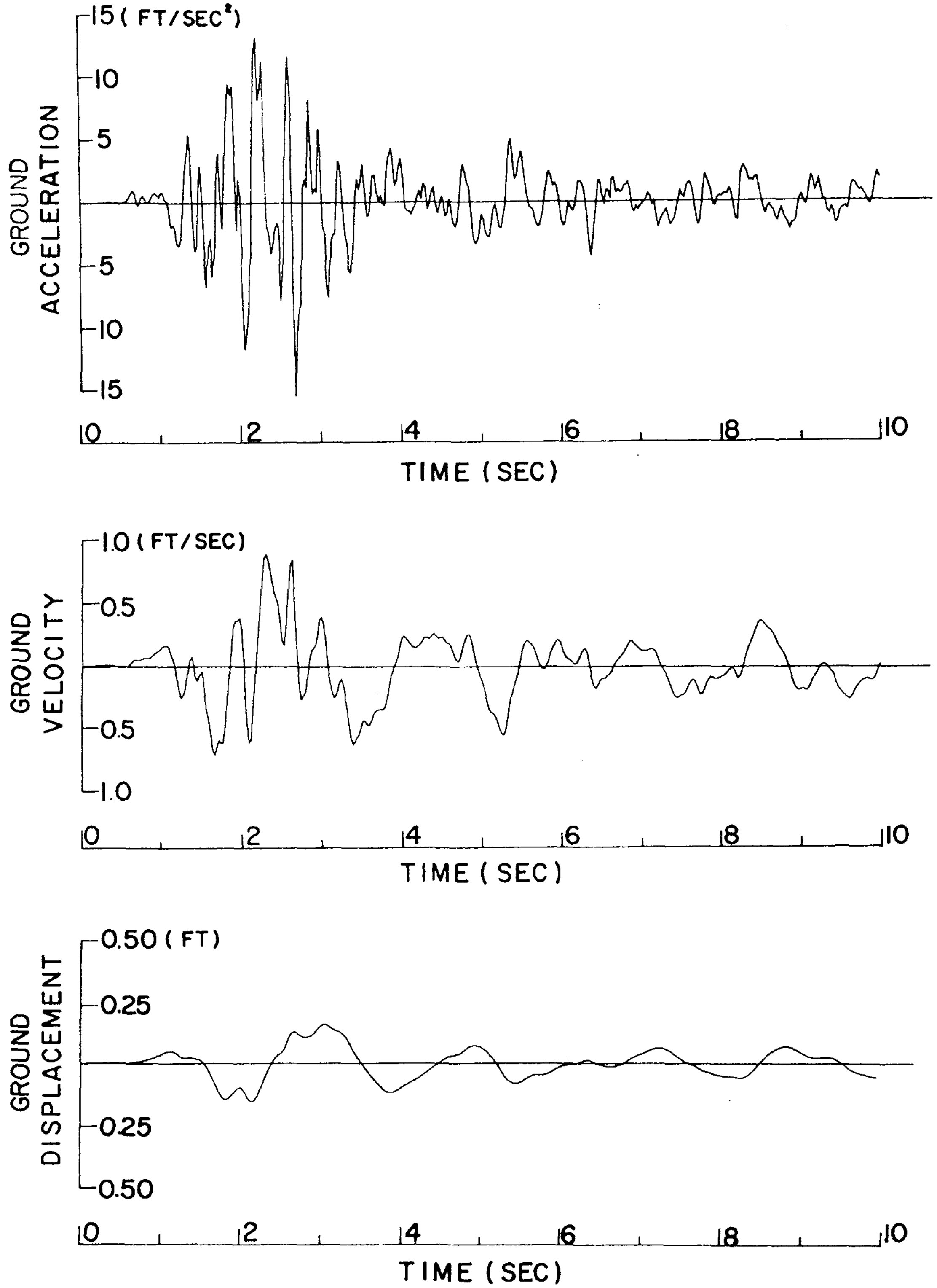
Before the synthetic accelerograms were developed, structural engineers had to rely on records of actual, recorded earthquakes for design analyses. The limitations of these actual earthquake records have been previously noted. Thus, the synthetic accelerograms provided an important new tool for the design of complex structures.

The accelerograms provided models of earthquakes representing a variety of duration, intensity, and frequency characteristics. Engineers were now able to identify the accelerogram that most nearly matched the special features of the design task at hand, and to use the accelerogram to analyze the response of a design structure under a variety of earthquake scenarios.

In summary, the development of synthetic accelerograms was based on research conducted over a span of seven years (about 1961 to 1968). The research led to an important contribution to the design of buildings in earthquake-prone areas. Since the mid-1960s, the results of the research have been used extensively by structural engineers, and have facilitated the design of numerous, complex structures that previously would not have been considered safe to build in earthquake-prone areas.

Figure 5

EARTHQUAKE D-1



SOURCE: Jennings, P.C., G.W. Housner, and N.C. Tsai, "Simulated Earthquake Motions," California Institute of Technology, Pasadena, Calif., April 1968.

NOTES TO SECTION II

[1] Jennings also recognizes fellowship support provided to him, in conducting this research, by The Ford Foundation and the General Electric Company.

[2] Interview with George W. Housner, October 31, 1983.

[3] Letter from George W. Housner to Gwendolyn B. Moore, dated October 16, 1984.

[4] The "tail" is the period of smaller shocks that follows the strongest portion of ground shaking.

III. THE USES OF SYNTHETIC ACCELEROGRAMS

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 the synthetic accelerograms 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, scientific or social science knowledge (Weiss, 1979). An enlightenment use could be said to "begin" when new knowledge raises awareness of certain issues, and be "completed" when such new knowledge becomes part of the popular vernacular (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, the accelerogram research could have served to make decisionmakers and others aware of the ability to use simulated earthquake records, in lieu of records of actual earthquakes, in analyzing the design of critical structures.

Decision-making use occurs when research helps to shape actual legislative initiatives, codes or 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. The accelerogram research could have been used in at least two ways: 1) for writing and adopting statutes, codes, or ordinances requiring the use of simulated earthquakes to analyze the design of certain structures; and 2) for developing standards guiding the use of simulated earthquakes in structural analysis.

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 also can be readily observed--i.e., in the actions of agencies, organizations, practicing professionals, or even individual consumers. The accelerogram research could have been used in practice by engineers to evaluate and modify the design of high-rise buildings, dams, nuclear power plants, and other critical structures.

In sum, each of these three types of potential uses represents some change in how individuals think about or act--or how organizations behave--with regard to new ideas produced through R&D. Of these, the Caltech research on synthetic accelerograms was potentially capable of being put to all three types of use. This full array of potential uses and users of the results of the accelerogram research is summarized in Table 1.

Actual Patterns of Use

The synthetic accelerograms developed at Caltech have been used extensively in the design and analysis of structures, and specific examples of all three types of use--i.e., practice, decisionmaking, and enlightenment--can be identified.

Practice Use. The synthetic accelerograms have been used extensively over a 15-year period to analyze the structural designs of specific buildings. Three such buildings, representing major types of structures, may be cited as follows. First, the synthetic accelerograms were an essential part of the design of the first high-rise building ever constructed in Los Angeles, as is described in Vignette No. 1.

Vignette No. 1: The Union Bank Square Building[1]

The Union Bank Square Building was the first high-rise structure to be built in Los Angeles, following the termination of the City Building Code's 150-foot height restrictions in 1959. The 42-story building was designed and constructed between 1964 and 1967, and contains 1,240,000 gross square feet.

Table 1

POTENTIAL USES OF THE RESULTS OF THE ACCELEROGRAM RESEARCH

TYPE OF USE	PRIMARY USERS
Enlightenment	
To increase awareness of the ability to use simulated earthquake records, rather than real ones, for design and analysis of structures	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 the use of simulated earthquakes in structural design	Elected, State and Local Officials
To develop standards guiding the use of simulated earthquakes	Code-Writing Bodies
Practice	
To analyze and design structures to withstand earthquakes	Engineers

> The earthquake resistance of the building is based on a "tube" design, in which the four exterior walls form a rectangular tube, composed of a gridwork of steel beams and columns. This form reflects the structural requirements recognized by using the "A-1" accelerogram and a dynamic analysis for design. According to the structural engineers involved, this design was very different from the one originally envisaged. Housner had been asked to participate in this analysis by the engineers who designed the building. The engineers knew of the accelerograms through contacts with Housner at meetings of the Structural Engineers Association of Southern California.
>
> During the 1971 San Fernando earthquake, the motions of the building were recorded, as well as the earthquake ground motions. This provided an opportunity to verify that: a) the simulated accelerogram was more intense than the actual earthquake motion, and b) the method of computing the response of the building to the A-1 accelerogram was, indeed, reliable. Figure 6 demonstrates the reliability of the method of calculation. In short, the building acted as predicted during the earthquake, and suffered no significant damage.

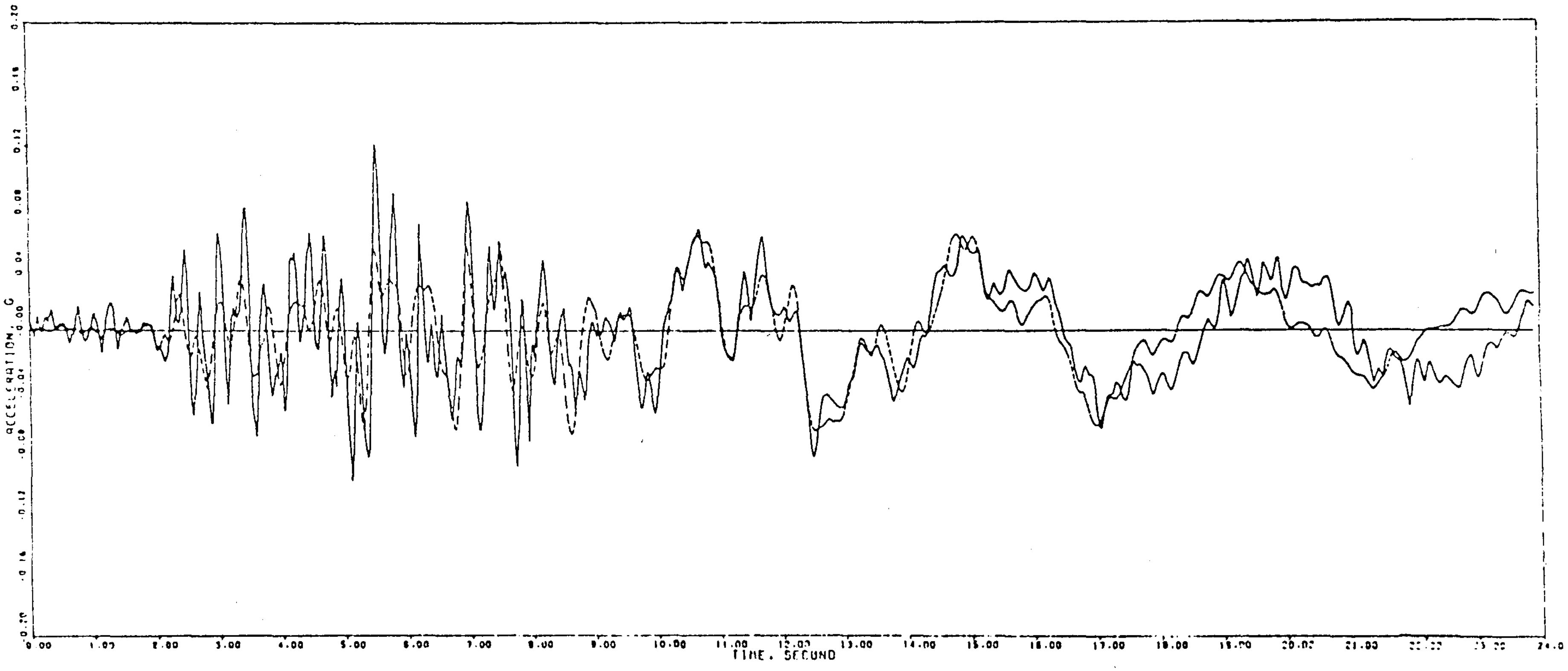
Another example of the early use of the accelerograms was in the construction of an off-shore drilling platform off the coast of Santa Barbara, described in Vignette No. 2.

Vignette No. 2: Off-Shore Drilling Platform[2]

> In 1968, the Exxon Research Lab was planning to build its "Hondo A" off-shore drilling platform in about 800 feet of water off the coast of Santa Barbara. In building the platform, the company sought a design that took into consideration the earthquake hazard in the Santa Barbara area. Because the state of knowledge for building an earthquake-resistant platform was primitive at that time, Exxon contracted with Housner and Jennings for assistance in the design. The synthetic accelerograms provided Exxon with a method for analyzing their designs. The Exxon staff used the synthetic earthquake records, because there were no relevant historical records available for use.

Figure 6

COMPARISON OF CALCULATED RESPONSE
TO ACTUAL RESPONSE OF UNION BANK BUILDING
(San Fernando Earthquake, February 9, 1971)



——— Recording of building motions during earthquake
------- Response calculated using the recorded building motion as input

SOURCE: Provided by R.C. Van Orden, with correspondence dated December 2, 1983.

> The platform was installed in 1976. It has resisted several small earthquakes since it was erected, and no damage has been sustained. The structure cost about $70 million, and the equipment that was put on the platform cost at least that much in addition.

The third example illustrates a recent use of the accelerograms in a very significant, "base isolation" structure. Base isolation is a new method used in the design of earthquake-resistant structures. The method is based on a ball-bearing principle, whereby huge rubber or steel "bearings" are placed between a building's foundation and its main structure, thus reducing the earthquake forces transmitted to the building. Vignette No. 3. describes how the synthetic accelerograms were used in the design of the first United States structure to use a base isolation design, and the biggest base isolation building in the world.

Vignette No. 3: Foothills Communities Law & Justice Center[3]

> The Foothills Communities Law & Justice Center is a 25,500 square foot, four-story facility constructed 13.5 miles from the San Andreas fault in Rancho Cucamonga, California. The building was constructed during 1983-84 for the County of San Bernardino.
>
> Because of its unique base isolation design, the building could not be a routine, code-designed structure, but required that special analyses be conducted. The firm of Taylor & Gaines of Pasadena, Calif., designed the facility, and a second firm--Reed & Tarick of San Francisco--conducted the structural analysis. The analysis included the use of the "A-1" synthetic accelerogram.
>
> The principal engineer on the project had previously read about the synthetic accelerogram research, and the County included Housner as a member of the advisory committee overseeing the design and construction of the facility.

Decision-Making Use. The results of the accelerogram research also have been used for decision-making purposes. Two examples illustrate this use. First, the California Department of Water Resources[4] specifies certain kinds of design criteria, to vendors, for the isolators (i.e., foundations) of power plant transformers to withstand earthquake ground motion. The design criteria were established using the synthetic accelerograms. Also, the accelerograms influenced the regulations used by the Nuclear Regulatory Commission in the design of nuclear power facilities.[5]

Enlightenment Use. The use of the accelerogram research for enlightenment purposes is still continuing to emerge. Three specific examples are relevant. First, practicing engineers appear to be generally aware of the research. Specifically, of the nine engineers contacted during the course of this case study, all were completely familiar with the accelerograms produced by Housner and Jennings at Caltech. Such knowledge is strong evidence of enlightenment use. In addition, both Housner and Jennings report receiving numerous inquiries about the synthetic accelerograms from practicing engineers, which is further evidence of enlightenment use. Second, there is evidence of enlightenment uses in other parts of the world. To illustrate this, Housner received an inquiry, in November 1983, from a scientist at the Soviet Institute in Moscow. The scientist was posing a question about earthquake resistant construction, and had addressed his correspondence to Jennings, Housner, and Tsai. Because these three individuals were the authors of the first report on synthetic accelerograms, the way the correspondence was addressed strongly suggests that the writer had a copy of this first report.

Third, Housner and Jennings recently completed a new monograph on earthquake design criteria (Housner and Jennings, 1982), which again describes the use of synthetic accelerograms for structural analysis. With such recent efforts, one might expect a continuing awareness of the accelerogram research.

Summary. The research on synthetic accelerograms has made a significant contribution to structural engineering. Examples of their use for practice, decision-making, and enlightenment purposes were found during the conduct of the present case study. The following section attempts to explain why this substantial utilization occurred.

NOTES TO SECTION III

[1] Based on an interview with Roy C. Van Orden and C. Eric Lindvall, Lindvall, Richter & Associates, Los Angeles, Calif., October 31, 1983; and on information provided by George W. Housner in his comments on the draft case study, dated October 16, 1984.

[2] Telephone interview with Jack Irick, Exxon Production Research, Houston, Texas, March 23, 1984.

[3] Interview with William C. Taylor, Taylor & Gaines Structural Engineers, Pasadena, Calif., November 11, 1983.

[4] Telephone interview with Les Harder, California Department of Water Resources, Sacramento, Calif., March 23, 1984.

[5] Telephone interview with Nilesh Chokshi, Structural Engineer, Structural Engineering Branch, Nuclear Regulatory Commission, March 23, 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 the use by the three preceding audiences.

The purpose of the present case study is to draw from the utilization experience of the synthetic accelerogram research, and 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 which 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 does help to explain the utilization of the synthetic accelerograms, in that evidence of the first of the two patterns was found. In their first article describing the synthetic accelerograms (i.e., Housner and Jennings, 1964), the researchers explicitly noted that their research had been conducted to "develop a practical method of constructing random functions [i.e., synthetic accelerograms] that can be used in place of [actual] earthquake accelerograms in making studies of the response of structures" (p.

114). Thus, the fact that the research addressed a previously defined problem may help to explain its widespread utilization. However, the second condition stipulated by the problem-solver model was not fully satisfied, in that the initial problem was not defined by any specific user, but represented the investigators' rendition of the situation.

The Research, Development, and Diffusion Model. The research, development, and diffusion model (RD&D) portrays 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 largely explains the utilization of the accelerogram research, in that all of the patterns associated with the model were evident in this case. First, the research was defined by the Housner and Jennings, without the influence of any other researchers or individuals. Second, the research was part of a stream of basic to applied research. Specifically, Housner initiated the research following years of earlier research on the mathematical properties of earthquake ground motion and the response of structures to earthquake shaking. Further, Housner and Jennings's initial accelerograms provided the basis for the development of more specific and refined accelerograms that reflect the special needs of a given site and structural design. Third, the accelerograms have been used as a product or service, offered by consulting engineering firms, from which commercial benefits are derived. Thus, the full pattern of the RD&D model is evident in this case study.

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 somewhat to further explaining the utilization of the research on synthetic accelerograms. Evidence of all three patterns associated with this model was found.

First, during the development of the synthetic accelerograms, both Housner and Jennings belonged to, and held prominent offices in, several professional organizations whose membership included potential users of the research. These included: the International Association for Earthquake Engineering (Housner was President from 1969-1973); the American Society for Civil Engineers (Jennings was Chairman, Structural Dynamics Committee, from 1969-1971); the Seismological Society of America (Jennings was President in 1980, and a member of the Board of Directors from 1976-1982); and the Earthquake Engineering Research Institute (Housner was President from 1954 to 1965, and Jennings was a member of the Board of Directors from 1968-1972). Housner and Jennings also were members of other organizations, including the Structural Engineers Association of California and the American Geophysical Union. Their participation in these organizations put them in constant contact with potential users of their research.

The second pattern associated with the social interaction model--communication between the producers of the knowledge and users during the research effort--also was evident in the present case. During the period when the research was being conducted, Housner, in particular, was routinely called upon to consult with practicing engineers where the research was directly relevant. In fact, the use of the accelerograms for the design of the Union Bank Building (see Vignette No. 1 in Section III) came about as a result of one of these consultancies. There is no evidence, however, that this interaction in any way influenced the conduct of the research or its ultimate outcomes, a condition further stipulated by the social interaction model.

Finally, the third pattern of the social interaction model--continuing communication between producers and users after a project is completed--is also evident in the present case. Both Housner and Jennings continued to be active in many different professional organizations after the synthetic accelerograms were produced. They also continued to consult, on a regular basis, with practicing engineers, public agencies, and private corporations on the design of structures and use of the accelerograms. Housner was a member of the National Academy of Engineering (NAE) throughout this period, and Jennings served on NAE panels and was subsequently elected to membership. All of these activities represent solid evidence of the continuing communication between the producers of the knowledge and users after the project was completed.

Summary. The nature and extent of the utilization of the synthetic accelerograms is largely explained by matching the pattern of events associated with the research to the patterns predicted by the RD&D model. Some further understanding is derived from the problem-solver and social interaction models.

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 activities associated with the synthetic accelerogram research 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 two activities for promoting utilization, associated with the problem-solver model, were apparent during the accelerogram research.

Activities Consonant with the RD&D Model. None of the activities associated with the RD&D model were undertaken in connection with the accelerogram research. Even though the RD&D model was prominent in explaining utilization in the present case study, the activities listed in Table 2 are not ones directly related to the conduct of a single project but rather focus on collections of projects and the activities of R&D funding agencies.

Activities Consonant with the Social Interaction Model. One of the activities for promoting utilization, associated with the social interaction model, was undertaken in connection with the accelerogram research: the active dissemination of the research results (11). Approximately 400 copies of the initial report (Jennings, Housner, and Tsai, 1968) were distributed. In addition, computer cards of the accelerograms were distributed upon request to numerous individuals, although no certain record of the number exists. Also, the results of the research were presented at the Fourth World Conference on Earthquake Engineering in 1969.

Summary. This section has pointed to several specific activities that can be undertaken to promote the utilization of research findings. Although only one of these activities was evident in the present case, these activities provide illustrations of how future policies might be designed to promote increased research utilization.

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.

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*These two activities are mainly undertaken by professional associations.

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 relating to the accelerogram research are reported here; 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 another 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 here.

[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 (1981). Second, a meeting was convened during the present 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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Appendix A

PERSONS INTERVIEWED FOR THE CASE STUDY*

Nilesh Chokshi, Structural Engineering Branch, Nuclear Regulatory Commission, Washington, D.C.

Les Harder, California Department of Water Resources, Sacramento, Calif.

George W. Housner, California Institute of Technology, Pasadena, Calif.

Jack Irick, Exxon Production Research, Houston, Texas

David Jeng, Structural Engineering Branch, Nuclear Regulatory Commission, Washington, D.C.

Paul C. Jennings, California Institute of Technology, Pasadena, Calif.

C. Eric Lindvall, Lindvall, Richter & Associates, Los Angeles, Calif.

Roger Scholl, John A. Blume Engineering, and the Earthquake Engineering Research Institute, Berkeley, Calif.

Malcolm Summerville, John A. Blume Engineering, Berkeley, Calif.

William C. Taylor, Taylor & Gaines Structural Engineers, Pasadena, Calif.

Roy C. Van Orden, Lindvall, Richter & Associates, Los Angeles, Calif.

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*Affiliations listed are those for interviewees at the time this case study was being conducted.

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Appendix B

SUMMARY OF THE PROCESS USED TO PRODUCE SYNTHETIC ACCELEROGRAMS

(Taken from Jennings, Housner, and Tsai, 1968, pp. 4-6)

GENERATION OF EARTHQUAKE MOTION

The simulation process used can be summarized as follows: A sequence of uncorrelated numbers, normally distributed with mean zero and variance unity is considered to be a collection of sample points of a white noise of a certain duration, sampled at an interval at least twice as short as the smallest period of interest in the final process. This approximation to a white noise is then passed through a second order filter whose properties are chosen to impart to the process the desired frequency content, as measured by the power spectral density.

By multiplying the resulting sections of a stationary Gaussian process by a suitably chosen envelope, the desired nonstationary properties are given to the record. In a manner identical to that used in processing real earthquakes (Berg and Housner, 1961), the baseline of the accelerogram is relocated by performing a least squares fit to the velocity of a parabolic correction to the baseline. This correction has the effect of filtering out long period components in the motion (with very small accelerations) which would otherwise impart unrealistic characteristics to the computed ground velocity and displacement. In real accelerograms these long period components are thought to arise from recording and digitizing errors; in the statistical model they are present because of the frequency content of the underlying process.

The parabolic correction to the baseline introduces an offset of the accelerogram at the beginning. For real accelerograms, this corresponds to the ground acceleration present at the time the accelerograph begins to record effectively. Because the simulated motions are intended to model perfectly recorded accelerograms, the acceleration must start from zero and this is accomplished by the addition of a small linear correction to the first second or half-second of the accelerogram.

The response spectra of the simulated earthquakes then were calculated so that their frequency contents could be examined and compared to that of recorded motions, where possible. Undesirable frequency components were then removed by passing the accelerogram through a second order filter, with a relatively long natural period. As employed, this filter progressively diminishes the frequency content of the record at periods longer than its natural period. Frequency components less than its natural period pass through the filter unaltered.

As the last step in the generating process the accelerograms of the different types were scaled to the intensity of shaking appropriate to the earthquakes with which they are associated. Finally the ground acceleration, velocity and displacement of the scaled motions were plotted and are presented herein along with the response spectra of the finished accelerograms.

RELATED PUBLICATIONS

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The following publications may be of further interest to the reader, and are available from COSMOS Corporation.

Yin, Robert K., Case Study Research: Design and Methods, Sage Publications, Beverly Hills, 1984. (available from Sage)

Yin, Robert K., The Case Study Method: An Annotated Bibliography, 1983-84 Edition, COSMOS Corporation, September 1983. ($7.00)

Yin, Robert K., Peter G. Bateman, and Gwendolyn B. Moore, Case Studies and Organizational Innovation: Strengthening the Connection, COSMOS Corporation, September 1983. ($15.00)

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