UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PROCEEDINGS OF CONFERENCE XLVII

A WORKSHOP ON

"USGS'S NEW GENERATION OF PROBABILISTIC GROUND MOTION MAPS AND THEIR APPLICATIONS TO BUILDING CODES"

OPEN FILE REPORT 89-364

Reston, Virginia

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A WORKSHOP ON "USGS'S NEW GENERATION OF PROBABILISTIC GROUND MOTION MAPS AND THEIR APPLICATIONS TO BUILDING CODES"

Sponsored by:

The Seismic Zonation Subcommittee of
the Structural Engineers Association of California
and
The U.S. Geological Survey

OPEN FILE REPORT 89-364

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

WORKSHOP ON "USGS'S NEW GENERATION OF PROBABILISTIC GROUND MOTION MAPS AND THEIR APPLICATIONS TO BUILDING CODES"

S. T. Algermissen and W. W. Hays
U.S. Geological Survey

and

J. P. Singh, Chairman
Structural Engineers Association of California
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On November 29-30, 1988, a representative of the Structural Engineers Association of California's Seismology Committee met with scientists and engineers of the U.S. Geological Survey (USGS) and a few invited guests to hear and discuss topical presentations related to the USGS's plans to produce a new generation of probabilistic ground motion maps. Experts on each technical component of probabilistic hazard mapping gave presentations and joined in the discussions (see Agenda). The overall goal was to identify the technical issues that need resolution so that they would not limit the application of the new maps in building codes and to forge a general agreement and plan for cooperation between the Seismology Committee and U.S. Geological Survey over the next several years.

The participants in the workshop recommended adoption of an action plan that would benefit both SEAOC and USGS. The proposed plan had the following achievable goals for 1989-1991:

1. Preparation of a draft action plan in 1989.

2. Development in 1989-1990 by USGS of preliminary map products based on spectral ordinates and other parameters for selected geographic areas (e.g., demonstration or pilot studies in portions of California, Utah, Mississippi Valley, Puget Sound, etc.).

3. Joint meetings in 1989-1990 involving a broad cross section of the professional community to review, discuss, and criticize the preliminary map products, seeking to reach consensus on critical issues.

4. Exchange of speakers from the Seismology Committee and USGS to enhance exchange of ideas and to enrich the research and applications process.

5. Publication of final map products that can be expected to be utilized in building codes.

This draft plan is now being implemented. Its full implementation will improve earthquake-resistant design throughout the Nation.

USGS-SEAOC Seismology Committee Meeting:
USGS New Generation Probabilistic Ground Motion Maps
and Their Applications to Building Codes

Sheraton at Fisherman's Wharf
San Francisco, California
November 29-30, 1988

Tuesday, Nov. 29, 1988

8:30 - 9:00 a.m.	(1)	Welcome and introductions Hays
9:00 - 10:00 a.m.	(2)	Briefings on ground motion mapping program of USGS and general requirements and concerns of SEAOC Algermissen, Singh
10:00 - 10:30 a.m.		(BREAK)
10:30 - 12:15 p.m.	(3)	How should the design earthquake be described (spectral shape, peak ground motion values, etc.)? Celebi, Leyendecker, Bertero, Carpenter
12:15 - 1:30 p.m.		(LUNCH)
1:30 - 3:15 p.m.	(4)	What probabilistic ground motion parameters should be mapped to meet the requirement of (2) above? Joyner, Campbell, Donovan, Idriss
3:15 - 3:30 p.m.		(BREAK)
3:30 - 4:30 p.m.	(5)	How should site effects be incorporated into ground motion estimates? Perkins, Seed

TENTATIVE AGENDA (CONTINUED)

Wednesday, Nov. 30, 1988

8:30 - 9:30 a.m.	(6)	How should the distribution of seismicity be specified (delineation of seismic source zones and earthquake rates)? Thenhaus, Stepp
9:30 - 10:30 p.m.	(7)	Treatment of parameter variability, minimum magnitude earthquake and attenuation variability. Bender, Johnson
10:30 - 11:00 a.m.		(BREAK)
11:00 - 12:00 a.m.	(8)	Probabilistic models Algermissen, Hart
12:00 - 1:30 p.m.		(LUNCH)
1:30 - 2:30 p.m.	(9)	Summary of conclusions of the workshop Algermissen, Singh
2:30 -		Continuation of meeting if required.

USGS/SEAOC Workshop
San Francisco, California
November 29-30, 1988

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WELCOME AND COMMENTS ON PROBABILISTIC GROUND MOTION MAPS

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U.S. GEOLOGICAL SURVEY (USGS) PROGRAMS

I am especially pleased to join with our cosponsor, the Seismology Committee of the Structural Engineers Association of California, in welcoming you to this meeting on "USGS's New Generation of Probabilistic Ground Motion Maps and their Application to Building Codes." This meeting provides a forum for discussing all facets of this important undertaking and for planning future cooperative activities.

The USGS, as the Nation's geologist and seismologist, manages and sponsors several hundred research projects each year that are designed to increase the fundamental base of knowledge and to develop methodologies for assessing and mapping the ground-shaking hazard throughout the Nation. These projects, conducted both internally by staff scientists and engineers and externally by scientists and engineers in academia and the private sector, through grants, are organized in five program elements:

1) Current Tectonics and Networks - The goal is to perform geologic and seismological analyses of current earthquake activity to define the seismic cycle of active faults and to estimate the earthquake potential in all parts of the United States.

   The recent report on "Probabilities on Large Earthquakes Occurring in California on the San Andreas Fault" is an example of work under this element.

2) Regional Earthquake Hazards Assessments - The goal is to create, compile, and synthesize new and existing data needed for making maps of the ground shaking, ground failure, and surface faulting hazards in broad geographic regions containing important urban areas.

   The National ground shaking hazard maps published in 1976, 1982, and 1988 (in press) and the studies underway along the Wasatch Front, Utah, and in the Puget Sound, Washington/Portland, Oregon, areas are examples of the work under this element.

3) Engineering Seismology - The goal is to deploy strong motion accelerographs to acquire records of strong ground shaking in free field locations and building response for a wide range of magnitudes, distances, and foundation materials.

   Accelerograms recorded in the 1977 Superstition Hills and Whittier-Narrows, California, earthquakes are examples of the work under this element.

4) Earthquake Prediction Research - The goal is to improve fundamental understanding of the physics of earthquake generation so that prediction of the time, place, magnitude, and probability of damaging earthquakes is technically feasible.

The prediction of a magnitude 6.2 earthquake between 1988-1991 at Parkfield, California, is an example of the work under this element.

5) Data and Information Services - The goal is to provide data on the occurrence of earthquakes throughout the world, especially those that have tectonic analogs in the United States.

The data provided after the September 19, 1985, Mexico earthquake is an example of the work under this element.

HISTORY OF GROUND-SHAKING HAZARD MAPS

The history of ground-shaking hazard maps in the context of building codes is nearly 50-year-long. The historical milestones include:

- o A map prepared by F. P. Ulrich in 1948 which remained in editions of the Uniform Building Code from 1949 until 1970.

- o A map prepared by S. T. Algermissen in 1969 that was incorporated, with some revisions, in editions of the Uniform Building Code from 1970 through 1988.

- o A probabilistic map of the peak horizontal bedrock ground acceleration of the contiguous United States produced by S. T. Algermissen and D. M. Perkins in 1976. This map represented a 50-year exposure time and a 90-percent probability of nonexceedance.

- o Maps of effective peak horizontal bedrock acceleration and velocity produced by Applied Technology Council in 1978 for a model building code. The map by Algermissen and Perkins serves as a technical guide.

- o Six maps of peak horizontal bedrock acceleration and velocity for exposure times of 10, 50, and 250 years prepared by S. T. Algermissen, D. M. Perkins, and colleagues in 1982. These maps contained more detail on the geologic and seismological characteristics of more than 100 seismogenic zones.

- o Six updated maps of peak horizontal acceleration and velocity prepared by S. T. Algermissen and colleagues in 1988 for the 1988 edition of the Recommended NEHRP provisions in Earthquake-Resistant Design. These maps incorporated the latest information on seismogenic zones, regional attenuation, and parameter variability on attenuation.

CRITICAL TECHNICAL ISSUES

Since large infusion of ground motion data in the San Fernando earthquake in 1971, researchers through the Nation have focused more and more on ways to resolve the critical technical issues inherent in construction of probabilistic ground-shaking hazard maps. Much progress has been made, but the following issues still remain:

- o Delineation of seismogenic zones, especially in the Eastern United States.

- o Maximum and minimum magnitudes.

- o Magnitude-frequency recurrence relations.

- "Near-source" problems, including directivity, focusing, breakout phrases, and the "killer" pulse.

- Soil response under strong ground shaking.

- Parameter variability.

We look forward to working with you to resolve these critical issues and other problems. With this meeting, we expect to create a process that will lead to the best possible new generation of probabilistic ground-shaking hazard maps that can be implemented in building codes.

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THE U.S. GEOLOGICAL SURVEY PROGRAM IN PROBABILISTIC GROUND MOTION ASSESSMENT

by
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The U.S. Geological Survey, since the inception of its program in probabilistic ground motion hazard assessment in 1973, has sought the advice of the engineering community in the development of ground motion maps for use in the earthquake resistant design provisions of building codes. This workshop is the latest effort of the USGS to: (1) provide the engineering community with information about changes, innovations and new initiatives in USGS probabilistic hazard mapping; and (2) obtain input from the engineering community concerning preferred ground motion parameters for code application.

The USGS program in probabilistic hazard assessment began in 1973 following the publication of a paper containing the general ideas of probabilistic seismic ground motion mapping and some prototype probabilistic ground motion maps of Utah and Arizona by Algermissen and Perkins in 1972. A probabilistic ground acceleration map of the contiguous United States was published by Algermissen and Perkins in 1976. This map of expected acceleration in rock in 50 years with a 10 percent chance of exceedance became the principal basis for development of the acceleration design map incorporated into the "Tentative Provisions for the Development of Seismic Regulations for Buildings" published by the Applied Technology Council (ATC, 1978). Maps of expected acceleration and velocity for periods of interest of 10, 50 and 250 years with a 10 percent chance of being exceeded were published in 1982 (Algermissen and others, 1982) and revised to include variability in attenuation and fault rupture length in 1988 (Algermissen and others, 1988). The 1988 maps will be included in the commentary of the new 1988 edition of the "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings" prepared by the Building Seismic Safety Council (BSSC) for the Federal Emergency Management Agency (FEMA) (1985).

This year we have begun the development of a new series of probabilistic ground motion maps which, it is hoped, will make use of research advances in seismotectonics and seismology since the 1982 USGS maps were published. In some areas, the research advances have been considerable. For example, much improved ground motion attenuation relations with standard deviations of about half of the standard deviations of the acceleration and velocity attenuation relationships used in the development of the 1982 and 1988 series of maps are now available. The reduced standard deviation means that there will be significantly less contrast between probabilistic ground motions calculated with and without this attenuation variability taken into account. Earthquakes, such as the 1983 Borah Peak, Idaho and 1987 Whittier Narrows, California earthquakes have provided much additional insight into problems of seismotectonics and ground motion mapping.

The objectives of this workshop from the USGS point of view are to (1) view and discuss the USGS plans and current work on a new generation of probabilistic ground motion maps; (2) identify, review and discuss the ground motion parameters that can be mapped effectively; (3) identify the most suitable parameters for use in the seismic design provisions of building codes, given the ground motion parameters that can be mapped; (4) discuss and evaluate the relative importance of various input parameters on probabilistic ground motion maps; and, (5) provide USGS with recommendations regarding their probabilistic ground motion mapping program with respect to the issues outlined above.

The most important objective of those listed above is, in my view, to reach a broad consensus on the optimum description of strong ground motion for building code applications, given the reality of the present strong motion data base and ground motion parameters that can realistically be mapped. If the concensus can be reached on this single objective, the workshop will have been, in my view, very successful. In addition, the workshop provides a unique opportunity for the exchange and development of ideas over a wide range of issues that are important in probabilistic ground motion assessment. Success of this workshop will assure the development of probabilistic ground motion maps whose design principles will be easily understood and can be readily adapted for use in national code maps.

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SEAOC CONCERNS AND REQUIREMENTS REGARDING GROUND MOTION MAPPING PROGRAM OF USGS

by

J. P. Singh
President, GEOSPECTRA, Richmond, California, and
Chairman, SEAONC Seismic Zonation Subcommittee

This workshop, the first in the planned series, was initiated at the request of SEAOC. The purpose of this and the remainder of the workshops is to develop the next generation means for representing ground motion for design and regulation process. This effort will require a great deal of interaction between geoscientists and engineers and will be greatly facilitated by development of USGS's New Generation of Probabilistic Maps and their Application to Building Codes. This first workshop is intended to be a planning meeting for answering these questions among others:

- o What concerns does SEAOC have with the current maps in representing ground motion estimates?
- o What are SEAOC's requirements for the next generation of maps?
- o How can USGS/SEAOC proceed to accomplish the desired goal?

The specifics of these items will be discussed by various participants during the workshop. Therefore, I would like to restrict my comments to a broader overview of these problems.

CONCERNS WITH THE CURRENT MAPS:

- Current maps are for rock sites only; out of the total population only a very small percentage of buildings are sited on rock
- Peak ground acceleration alone is a very poor parameter for use in structural design and in reconciling structural damage
- Treatment of uncertainity is unclear; it appears that the uncertainity is considered more than once
- Seismic Source Zones and the Attenuation Relationships used are fairly old and, in many instances, are no longer applicable

REQUIREMENTS OF SEAOC:

The information required for structural design and regulation can be put into two broad categories:

a. Basic Design Parameters
b. Performance Related Design Parameters

Basic Design Parameters: The basic design parameters usually form the basis for simple code type approach. These parameters are intended to satisfy design requirements of a large population of standard structures sited on standard soil sites and excited by standard earthquake ground motions and, in general, are based on adequate building perfomance data from large number of buildings. The ground motion input prescribed in the 1988 UBC is a good example of the basic design parameters. Here, the the standard site-dependent spectral shapes together with appropriate reduction factors are utilized to develop the base shear for design of structures. Such types of inputs are inadequate where factors such as structural configurations, structural systems, construction techniques, non standard site conditions and/or non standard ground motions may result in performance levels different than those intended in the codes.

Performance Related Design Parameters: The performance related design parameters are more specific to sites and/or structures. Use of such parameters becomes imperative where the architectural, construction method, site and ground motion constraints require design beyond the minimum code requirements. In such cases where the design philosphy starts to deviate from the standard code practices the often asked question is " why the difference from building code?". This is particularly true if the site specific design indicates short- and/or long-term cost increases. In such cases, the simple arguments that codes are minimum requirements for design of standard structures sited on standard soils subjected to standard earthquake usually do not suffice. Therefore, it is important that the next generation of mapping be more site specific (i.e. include spectral content and estimates of ground motion duration). Such an endeavor will provide somewhat more convincing arguments for deviations from basic design parameters. Such mapping should properly consider the effects of source, travel path and soil conditions. Because the extent of damage to buildings due to irregularities in layout or due to strength discontinuities, to a large extent, is related to long period part of the ground motion, it is important that proper estimates of long period motions due to source size, nearfield effects, soil and basin effects be made.

HOW TO ACCOMPLISH THIS GOAL;

We need to follow up this planning workshop with a series of workshops to steer our course in the right direction.

REMARKS RELATED TO DESCRIPTION OF DESIGN OF EARTHQUAKES

by
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First and foremost, whatever is decided upon should be simple and explainable.

Secondly, I believe it is impossible to think of the description of a design earthquake without spectral shape. However, the spectral shape should not be limited to scaling with ZPA or any form of peak ground acceleration. The parameters that control the shape of the response spectra could be specified by the following general factors:

a. Geological environment (described as in the existing soil factors $[S_i]$ in the new version of SEAOC and 1988 UBC).

b. Spectral peak accelerations that are dependent on:

i. frequency bands

ii. Location of the site with respect to proximity to a fault system, a specified magnitude earthquake expected with a designated probability of non-exceedance and return period, and the related attenuation relationship (which may be different for western and eastern earthquakes)

iii. specific known conditions (specific geotechnical and topographical conditions)

THE DESIGN EARTHQUAKE - SOME ISSUES FOR DECISION

Edgar V. Leyendecker
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INTRODUCTION - The U.S. Geological Survey is currently working on preparation of the next generation of seismic hazard maps. In the past the USGS maps of ground motion have been maps of peak values. However, we have moved from a single map of peak acceleration at one exposure period (Algermissen and Perkins, 1976), to maps of peak acceleration and velocity at several exposure periods (Algermissen and others, 1982). It is recognized that the peak values are not necessarily what should be used directly in structural design. Part of the current effort, such as this workshop, includes obtaining additional engineering input on the ground motion parameters that should be mapped that will be most useful for code application. Complete agreement is not expected on all details at this workshop, but it is hoped that the "wish list" can be narrowed to a manageable degree. In reaching agreement consideration must be given to both technical and non-technical factors involved in modifying codes. As a number of the workshop participants know, the non-technical factors can override the technical ones. We have to consider that code changes tend to occur in steps rather than leaps. A major or complicated change is likely to get nowhere unless it can be shown to be a life safety matter.

NATIONAL REQUIREMENTS - It is important to remember the national influence of the Structural Engineers Association of California (SEAOC) on seismic design - through its own publications (e.g., SEAOC, 1985) and adoption and/or consideration of its recommendations, in whole or in part, in documents such as the Uniform Building Code (UBC) (International Conference of Building Officials, 1988). Since the UBC is widely used it is obvious that the SEAOC influence goes well beyond state boundaries. Thus SEAOC, while preparing recommendations to achieve seismic safety in California, have people and organizations outside the state trying to have their views considered in SEAOC recommendations. While this is a compliment to the organization, it places an additional burden on it. The USGS, as a Federal agency participant in the national earthquake program, while working with local organizations such as SEAOC, must balance the needs and desires of the local organization against the needs and desires of the national program in the products it produces.

CODE TRENDS - Recent trends in earthquake design of "typical" buildings have been toward the use of more realistic measures of ground motions in the design process. In building code type recommendations this began with the 1978 report, Tentative Provisions for the Development of Seismic Regulations for Buildings (Applied Technology Council, 1978) and has continued with the 1985 and 1988 NEHRP provisions (Building Seismic Safety Council, 1986 and 1988) and indirectly in the 1988 Uniform Building Code. Other model building codes (Building Officials and Code Administrators, 1987 and Southern Building Code Congress International, 1987) and standards (American National Standards Institute, 1982) are moving in this same direction.

Included in this approach of more realistic ground motion is the recognition that use only of peak values of parameters such as acceleration and velocity are not entirely appropriate for design purposes. Duration, etc play major roles and are considered in preparing code recommendataions.

In some cases (e.g., Applied Technology Council, 1978) the peak value maps have been adjusted by others to become "effective peak value" maps for use in design. Although "effective peak values" are clear enough in concept, they suffer from a precise definition and they have caused confusion in some geographic areas. For example, if the "effective peak value" contours in the commentary of the NEHRP 88 are examined it appears to many users that California is not so much different than some other areas of the U.S. This is particularly true since, at least to the casual observer, only California contours appear to be reduced by the use of "effective peak values". Contours in most other geographic areas remain at or near the peak value level. Part of the rationale given, at least for California is that the ductility requirements (and tighter inspection requirements) are more important than using higher values of ground motion parameters. This, in turn, raises the response in other geographic areas that they must provide both ductility and resistance to peak values. Why can't they also lower the mapped peak values to some smaller effective peak value? This is not to say that ground motion values, combined with other requirements, that have been carefully evaluated for use in California are not appropriate for the state. It does suggest that the national picture needs to be carefully examined and the rataionale for recommendations clearly explained.

One approach was tried in the NEHRP 88 by providing an alternative to the concept of "effective peak values" used in ATC 3-06 and NEHRP 85, although the use of "effective peak values" continues as the main approach in NEHRP 88. The alternative approach, which is on a trial-use basis uses 1987 USGS maps of peak acceleration (in %g) and velocity (in cm/sec). An upper limit is permitted to be placed on the values obtained from the maps. Base shear equations are modified to use these values directly. The upper limit on input values keeps the answers from differing greatly from those obtained using "effective peak values." This approach was taken in part because it is compatible directly with USGS maps and because it presented a clearer national picture of the hazard than a map with "effective peak values."

As an example of what can be mapped to improve on the current situation, yet is practical, consider Bill Joyner's suggestions (this volume). He proposes mapping spectral values at 0.2 and 1.0 seconds. This results in a small number of maps so it is manageable from technical and production aspects. There are some specific reasons for suggesting these values from a ground motion point of view. These reasons are discussed in more detail by Joyner and Campbell (this volume). This approach also appears reasonable from an engineering point of view and should be carefully discussed. More values may be required but this would in turn also require more maps.

There needs to be discussion on the exposure periods and the performance criteria. Currently codes are based roughly on ground motion maps with a ten percent probability of exceedance in 50 years. Designers in some regions of the U. S. where the recurrence interval is long for large earthquakes have expressed concern that using a ground motion for a short recurrence interval is not right for them. Other maps could just as easily be prepared, such as those in the NEHRP.

Is it time for a two-level design approach, one for serviceability and one for strength (remember that code documents are considered life safety documents)? Perhaps the two are close for California, they are probably not for the rest of the U. S. If this receives serious consideration, then it may be appropriate to review the well-known SEAOC statements describing what their recommendations are trying to achieve. Finally, how should our requirements for strengthening of existing buildings differ from new buildings?

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HOW SHOULD THE DESIGN EARTHQUAKE BE DESCRIBED?

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General Goals in Seismic Resistant Construction: The philosophy of earthquake-resistant design for buildings other than essential facilities has been well established and proposed to prevent nonstructural damage in frequent minor earthquake ground shakings, to prevent structural damage and minimize nonstructural damage in occasional moderate earthquake shakings, and to avoid collapse or serious damage in rare major ground shakings. This philosophy is in complete accord with the concept of **comprehensive design.** However, current design methodologies fall short of realizing the objectives of this general philosophy.

In a comprehensive design approach, it should be recognized that building damage may result from different seismic effects: (1) ground failures due to fault ruptures or to the effects of seismic waves; (2) vibrations transmitted from the ground to the structures; (3) tsunami and tsunami-like disturbances and seiches in lakes; and (4) other consequential phenomena such as floods and fires. **The seismic effect that usually concerns the structural engineer and is taken into account by seismic-resistant design provisions of building codes is vibration of a building in response to ground shaking at its foundation.** Thus, the first step in the design procedure of a future building should be analysis of the suitability of the site selected for the building.

From the above discussion it is clear that microzonation of a region should concentrate on: (1) geologic considerations that permit the location (mapping) and identification of the type (features) of the seismic faults on the neighborhood of the region in question; and (2) on the seismological aspects that allow the estimation of the occurrence rate and spatial distribution of earthquakes together with their magnitude, and on geotechnical considerations. Among the more pertinent parameters that should enter into microzonation are those concerns with soil liquefaction, soil densification, soil strength, and dynamic soil properties, such as shear and damping.

Specification of Design Earthquakes: The design earthquake (DEQ) depends on the design criteria, i.e., the limit state controlling the design. Conceptually, the design earthquake should be that ground motion that will drive the structure to its critical response. In practice, the application of this simple concept meets with serious difficulties, first because there are great uncertainties in predicting the dynamic characteristics of ground motions at the building site, and second because even the critical response of a specific structural system will vary according to the various limit states that could control the design. Although a Comprehensive Design should consider all possible limit states that a structure may go through during its life, for standard buildings it is usual to consider just the following three limit states: serviceability level - where the building is expected to continue to perform its designated function; damageability level - where the damage is limited to predetermined levels; and safety against collapse - where any degree of damage that will not endanger human life is permitted. Furthermore, in building design usually only the serviceability and collapse limit states are considered. Once the appropriate design criterion has been selected the DEQ can be defined using different degrees or levels of sophistication depending on the purpose for which it has to be defined. Although the ultimate goal is to arrive at a reliable but simple definition of DEQ which can be used to establish the minimum seismic code requirements for the design of standard buildings located on standard sites, it is obvious that to achieve such a goal it will be necessary to supply all the necessary data to the experts in the field of geotechnical and structural engineering who are involved in formulating the code design regulations so that they will be able to arrive at simple but reliable definitions of DEQ. The data needed for the different limit states are briefly discussed below.

Information Needed by Geotechnical Experts: Ideally, for each type of site (zone) of a given urban area, these experts need the time histories of the six components of the Earthquake Ground Motions (EQGMs) that at different intensity levels may occur at the base rock of such site or zone. Each different EQGM intensity should be accompanied by the corresponding frequency of occurrence. For standard buildings it will be sufficient to have just the time histories of the three translational components.

Based on the above received information and considering the available database on recorded motions at free field surface as well as at the foundation of buildings, the geotechnical experts should predict the time histories of the EQGMs at different intensity levels that may take place at the level of the foundation of the buildings with their corresponding frequency of recurrence.

Information Needed by Structural Experts: These experts need the time histories of at least the three translational components of the EQGMs that can occur at the foundation of the building at different intensity levels and with the corresponding frequency of occurrence. With this information the structural engineering experts have to specify the design earthquake according to the limit state controlling design of structures.

Design Earthquake (DEQ) for Serviceability Limit States: For all practical purposes, the building should remain in the linear elastic state. While a DEQ based on a smoothed linear elastic design response spectrum (LEDRS) is the most reliable and convenient approach for the preliminary design, the ground spectrum that is used to derive the LEDRS must be appropriate to the site and not based just on standard values. Values selected for the damping ratio, determination of allowable stresses, and computation of natural periods and internal forces must be consistent with expected behavior.

Design Earthquake (DEQ) for Ultimate Limit States (Safety Against Dangerous Damages or Collapse): The preliminary design of essential facilities, which should remain essentially undamaged (elastic) even for the most severe ground motions expected at a certain site and which are usually termed the Maximum Credible Earthquake Ground Motions (MCEQGMs), should be based on a smoothed LEDRS which reflects the dynamic characteristics of the expected MCEQGMs at the given site. However, except for these essential facilities, it would be unrealistically conservative and uneconomical to design most building structures to respond to MCEQGMs at the site within the linear elastic range of the structural material, or even in the so-called effective linear elastic range of behavior of the structure (i.e., to its significant yield level). In order to realize economical design of buildings that could be subjected during their service life to MCEQGMs, significant but controllable (acceptable) inelastic deformations of such buildings must be accepted. These inelastic deformations usually allow the required linear elastic strength to be reduced without the maximum resulting deformation increasing significantly.

A very convenient approach to the preliminary design of structures allowing for inelastic deformations is through the use of smoothed Inelastic Design Response Spectra (IDRS). Derivation of reliable IDRS requires full characterization of the expected severe ground motions at the site as well as what constitutes acceptable structural responses. However, current methods used to calculate IDRS do not account for the duration of strong ground shaking. Extensive integrated analytical and experimental studies will be required to obtain the information necessary to establish reliable design earthquakes when ultimate limit states control the design. Until this is done, the procedure suggested in Refs. 1 and 2 can be used. This procedure requires the derivations of inelastic response spectra corresponding to the available recorded ground motions through nonlinear dynamic time history analyses of structures with different degrees of displacement ductility ratio. The advantages of deriving and specifying a series IDRS for different values of the displacement ductility ratio is that it tells the designer that proper inelastic design is a trade off between yielding strength and ductility (damage).

<u>Energy Approach</u>: It has been pointed out above that current methods of deriving IDRS do not account for the duration of strong shaking. This duration plays an important role in the degree of damage that a structure will undergo. The author believes that the future of earthquake-resistant design is on an energy approach. This approach is based on the following energy balance equation:

$$E_I = \underbrace{E_K + E_S}_{E_E} + \underbrace{E_H + E_{\xi}}_{E_D}$$

$$E_I = E_E + E_D$$

<u>Earthquake Energy Input, E_I</u>: For any given EQGM, its E_I is the most reliable parameter that measures its damage potential. This damage potential parameter depends on the dynamic characteristics of both: the shaking of the foundation; and the whole soil-foundation-superstructure system. Therefore the structural engineering experts need to have at their disposal reliable prediction of the severe ground motions that can occur at the foundation of the structure. In the studies reported in Refs. 3 and 4, the E_I spectra have been computed for many recorded ground motions applied to single degree of freedom systems (SDOF), with linear elastic-perfectly plastic behavior for different values of the ductility ratio μ, and the damping ratio ξ. In Ref. 4 it is shown that while the linear elastic pseudovelocity (S_{pv}), which has been proposed as an index to represent the damage potential of an earthquake, can be used to obtain a lower bound to the input energy spectra, it may significantly underestimate the true input.

Concluding Remarks

. The design earthquake (DEQ) depends on the design criteria. At least two levels of DEQs should be specified: one for service limit state; and the other for ultimate (safety against dangerous damage and/or collapse) limit states.

. For preliminary design of structures the most convenient and rational manner to describe the DEQs is through Smoothed Design Response Spectra: LEDRS and IDRS.

. For any given urban area in order to mitigate EQ hazards it is necessary: to improve its microzonation; and to supply geotechnical and structural engineering experts with reliable information regarding expected time histories of EQ ground motions (EQGMs) at the base rock as well as at the free field surface and at the foundation level of structures. These expected time histories of EQGMs should be at different intensity levels and with the corresponding frequency of recurrence.

. There is need to estimate the E_I of the expected EQ motions of the foundation of different types of structures, in order to select the critical ground motions and to formulate reliable IDRS for such structures.

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COMMENTS ON HOW THE DESIGN EARTHQUAKE SHOULD BE DESCRIBED

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Current mapping in 1988 UBC is based on recorded seismicity and influenced by fault movement and expectations based on geological evidence. This direction should be continued, but enhanced significantly by the local California on and off shore information and the computer simulation capabilities which appear to be recently very successful.

Eastern US and other areas of the US/Canada/Mexico/Japan should be similarly mapped in the same direction based on the best information available in order to develop a global perspective on local US seismicity and more global interaction of professionals.

"Near-field" effects need to be more defined based on limited field data but with computer simulation to expand data. Development and feasibility of special fault zones could be a result or modifications to design procedures, if needed.

The basic direction of probability based spectra is necessary and two levels of spectra are needed in order to evaluate the collapse/stability stage of structures as well.

Preferably, the definition of spectra and dynamic analysis could be developed to avoid the scaling of dynamic results to quasi-static base shears and use the results of analysis more directly. Hopefully, definition of structural parameters and response could be developed in parallel to the point where "R_W" is not part of the "Code Level" development forces.

The UBC Code (1988) uses the term "MAJOR EVENT" and defines it as effective peak (rock) acceleration with a probability of occurrence of 10 percent in 50 years (about 475 year recurrence interval). Discussion is needed of current terms in use, perhaps incorrectly, of Maximum Probable Earthquake, Maximum Credible Earthquake, Service Level Earthquake, Collapse Level Earthquake, Maximum Expected Earthquake, etc.

Different recurrence intervals are currently used for Design Earthquakes by different groups (72 year, 200 year, 475 year, 1000 year and higher) and needs further probabilistic review and correlation with structural response.

Long period structures are typically high rise buildings and tend to have the most extensive analysis and design versus low rise and smaller buildings. Consequently, the 2/3 exponent on period T may not need to be used to develop conservatism in design of taller buildings.

Finally, earthquake duration, repetitivity of strong shaking magnitude and soil structure interaction need fu ther refinement and inclusion in mapping and design.

SUGGESTIONS REGARDING PROBABILISTIC GROUND-MOTION MAPS FOR USE IN BUILDING CODES

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One of the first questions to be addressed in planning probabilistic ground-motion maps for use in building codes is what ground-motion parameters should be mapped. Fundamentally the choice is one that belongs to the structural engineers, but it should be made in consultation with seismologists, who may have special insight into how the different parameters may vary with magnitude, distance, and site conditions and how the different parameters may be correlated with each other. Simplicity of application is obviously an important consideration in making the choice.

Previous choices were peak horizontal acceleration or peak horizontal acceleration and velocity, which were used as indirect indicators of short-period and intermediate-period response spectral values. There are a number of reasons for rejecting these options. Because the seismic spectrum in the eastern U.S. may extend to higher frequencies than in the West, the factor relating peak acceleration to short-period response in the range above $0.1s$ may differ in the East from what it is in the West. The factor relating peak velocity to intermediate-period response varies significantly with magnitude and site conditions as indicated by the predictive equations of Joyner and Boore (1982) for response values and for peak velocity. There is really no point in using peak horizontal acceleration and velocity as indicators of response spectral values when response values themselves could just as well be mapped directly.

My suggestion for parameters to be portrayed on the ground-motion maps are $0.2s$ and $1.0s$ pseudoacceleration response (PSA) at 5 percent damping. Admittedly these parameters represent the response of damped elastic systems and do not incorporate the nonlinear response to be expected from real structures at high levels of motion. Response reduction factors, different for different structural types, would be applied to account for nonlinear response (Cornell and Sewell, 1987). The $0.2s$ response was chosen to represent the short-period response because it is more or less in the middle of the short-period range. The $1.0s$ response was chosen to represent the longer-period response because the peak of the pseudovelocity response spectrum is generally near $1.0s$ (Joyner and Boore, 1982). Equations for estimating $0.2s$ and $1.0s$ response are available now (Joyner and Boore, 1988), and improved equations can be expected in time for making the proposed ground-motion maps. I urge that the maps be made for the S_2 soil condition because that is the condition for most of the strong-motion data upon which the equations for estimating ground-motion values are based. Other site conditions would be taken care of by the S factor.

If the code is to be in the same form as in the 1988 UBC, then the equations would be

$$Z_1 = \text{PSA at 0.2s and 5 percent damping}$$

$$Z_2 = \text{PSA at 1.0s and 5 percent damping}$$

$$ZC = \frac{Z_2 S_i}{T^{2/3}}$$

except that ZC need not exceed Z_1.

$$S_2 = 1.0$$

$$S_1 = 0.8$$

$$S_3 = 1.25$$

$$S_4 = 1.7$$

There are special problems in making the maps in the eastern U.S. Different equations may be necessary for estimating the ground-motion parameters. I suggest that some consideration, at least, be given to the equations that have been developed using stochastic source theory (Boore and Atkinson, 1987; Toro and McGuire, 1987), though these equations may need to be modified to correspond to the appropriate site condition. The whole question of defining appropriate site types may need reexamination for the East. Furthermore, recent unpublished work by T. C. Hanks and D. M. Boore indicates that magnitude assignments for pre-instrumental eastern U.S. earthquakes need revision.

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PROPOSED REVISIONS TO THE UNIFORM BUILDING CODE: ISSUES RELATED TO THE SPECIFICATION OF GROUND MOTION

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Introduction

Building codes use a lateral-force coefficient—usually a fraction of the weight of a building—as a means of including earthquake forces in the computation of design base shear. Historically, the lateral-force coefficient has been used to quantify the relative difference in expected ground motion for specific seismic zones in the United States, its value set by the experience and judgement of practicing engineers. With the 1988 edition of the Uniform Building Code (UBC), the lateral-force coefficient has become integrally tied to recorded ground motion. Commentary in the 1988 edition of the Structural Engineers Association of California (SEAOC) "Blue Book", on which the 1988 UBC is based, suggests that the Z coefficient—the ground-motion component of the lateral-force coefficient—should correspond to ground-motion values that have a 10 percent probability of being exceeded in 50 years.

By basing lateral forces on a probabilistic estimate of ground motion, the 1988 UBC has incorporated the concept of uniform hazard in the routine design of buildings. SEAOC, together with the U.S. Geological Survey, has proposed to extend this concept further in the next revision of the UBC by adding two refinements to the seismic provisions of the existing building code. The first refinement is to use a seismic hazard map rather than a set of discrete zones to define levels of probabilistic ground motion throughout the United States. The second refinement is to use a uniform hazard spectrum—a response spectrum having a uniform probability of exceedance at all periods—to characterize the design response spectrum. Both of these refinements are based on well-accepted earthquake engineering principles.

The current version of the national seismic hazard map (Algermissen *et al.*, 1982) provides probabilistic estimates of peak acceleration and peak velocity. No similar map is as yet available for response spectral ordinates. Although there are techniques available for developing response spectra from peak ground-motion parameters (e.g., see Campbell, 1987a), there is considerable debate as to whether such spectra represent realistic design response spectra. Some engineers and seismologists believe that the only correct means of estimating a uniform hazard spectrum is to construct it from probabilistic estimates of response spectral ordinates. Although the concept of a uniform hazard spectrum is well-accepted in the earthquake engineering community, the use of such a spectrum to characterize probabilistic ground motion introduces added complexity to the development of a seismic hazard map. A typical seismic hazard map has two dimensions—displaying the geographic distribution of ground-motion with contours. However, the spectral nature of response spectra adds a third dimension—frequency—that requires a separate seismic hazard map for each frequency of interest.

The intent of this paper is to present and discuss issues related to the specification of ground motion for consideration in the next revision of the UBC. Specific topics of discussion include alternative techniques for defining design response spectra, the selection of strong-motion attenuation relationships for seismic hazard mapping, variations in the regional characteristics of ground motion, and the definition of site coefficients.

Techniques for Estimating Design Response Spectra

Over the years engineers have proposed a variety of techniques for developing design response spectra (e.g., see Campbell, 1987a), three of which have been used to develop uniform hazard spectra: (1) using a probabilistic estimate of peak acceleration to scale a response spectral shape, (2) using probabilistic estimates of peak acceleration and peak velocity to scale short-period and intermediate-period spectral amplitudes, and (3) constructing a response spectrum from probabilistic estimates of response spectral ordinates.

Techniques Based on Peak Acceleration. Using peak acceleration to construct a uniform hazard spectrum has many advantages: it is widely available, it is easily computed from existing attenuation relationships, it is easily mapped, and it can be compared with previous estimates of probabilistic ground motion (e.g., Algermissen and Perkins, 1976; Algermissen *et al.*, 1982). However, it has one major weakness that makes it ineffective as a spectral design parameter: it does not correlate well with the intermediate- to long-period ordinates of response spectra (e.g., Campbell, 1988a; Joyner and Boore, 1988). As a result, it cannot adequately represent the magnitude and distance dependence observed in uniform hazard spectra (e.g., Bender and Campbell, 1989).

Another disadvantage of peak acceleration is its dependence on regional differences in the high-frequency limit of ground motion, or so-called f_{max}. In California, the effective limit of observed high-frequency energy is on the order of 3–20 Hz, and in Eastern North America (ENA) it is as high as 30–50 Hz (Campbell, 1989). This regional difference in f_{max} can lead to higher peak accelerations in ENA than in California for otherwise similar ground motions.

One possible means of mitigating the effects of f_{max} would be to limit the frequency bandwidth of the ground motions used to define peak acceleration to around 10 Hz, thereby reducing the impact of high-frequency energy in the recordings. This could be accomplished by scaling peak acceleration from a recording (or simulated recording) of a standard accelerograph, such as the SMA-1 (Campbell, 1989), or by defining a pseudo peak acceleration which has a fixed ratio with respect to a specified short-period spectral ordinate.

In either case, it would then be possible to use the same spectral shapes to characterize ground motions throughout the United States.

Another means of dealing with regional differences in f_{max} would be to incorporate it directly into the development of uniform hazard spectra by explicitly including it in both the estimation of peak acceleration and response spectral shape. Although more satisfying from a seismological point of view, this approach would create an undesirable complexity in the development of seismic hazard maps.

None of these proposed approaches for dealing with f_{max} is completely satisfactory. The mere fact that peak acceleration depends so strongly on f_{max} and that it cannot adequately characterize intermediate- to long-period spectral ordinates severely limits its usefulness as an engineering design parameter.

Techniques Based on Peak Acceleration and Peak Velocity. Aside from peak velocity not being as readily available as peak acceleration, it shares many of the same advantages and disadvantages as peak acceleration when used as a design ground-motion parameter. However, together these two parameters have a major advantage that neither possesses alone. Newmark and Hall (1982) found, by using peak acceleration, peak velocity, and peak displacement to develop a design response spectrum, that they could obtain a reasonably realistic dependence of spectral shape on magnitude, distance, and site conditions.

By its very nature, the Newmark-Hall spectrum has an extremely simple shape. In order to scale the short-, intermediate-, and long-period bands of the spectrum by peak acceleration, peak velocity, and peak displacement, these bands must be characterized by constant amplitude. The result is a pseudorelative velocity (PSRV) response spectrum whose shape is characterized by the intersection of several straight-line segments. This implies that any probabilistic response spectrum developed by this technique will not be a "true" uniform hazard spectrum, and that buildings designed to such spectra will exhibit slightly different degrees of conservatism depending on their fundamental period.

A disadvantage of using peak velocity to scale the intermediate-period band of a response spectrum is the observed difference in scaling characteristics between peak velocity and intermediate-period spectral ordinates. For example, Campbell (1988a) has found that peak velocity scales with sediment depth, but that PSRV spectra up to periods of 1.5 sec do not. Both Joyner and Fumal (1985) and Campbell (1988a) have found that peak velocity scales differently with magnitude and distance than do intermediate-period ordinates of PSRV spectra. Also, since the Newmark-Hall technique requires the use of peak acceleration to scale the short-period ordinates of the spectrum, it retains the problems associated with f_{max}.

Techniques Based on Selected Response Spectral Ordinates. The use of probabilistic estimates of response spectral ordinates to develop a uniform hazard spectrum averts virtually every major disadvantage associated with the use of peak acceleration and peak velocity. As a result, it would appear to be *prima facie* the best technique for defining a design response spectrum. There are, however, several disadvantages to mapping spectral ordinates: they are not as widely available, they are not as easily computed from existing attenuation relationships, they require the development of multiple seismic hazard maps, and they are not easily compared with previous estimates of probabilistic ground motion (e.g., Algermissen and Perkins, 1976; Algermissen *et al.*, 1982).

A true uniform hazard spectrum requires at least five or ten spectral ordinates to define its shape. However, too many parameters will tend to overly complicate the procedures used to develop a design response spectrum. As a compromise, two response spectral ordinates could be used to generate a uniform hazard spectrum using a modified Newmark-Hall technique. One spectral ordinate would be used to scale the short-period part of the spectrum and a second would be used to scale the intermediate-period part of the spectrum.

In this approach, the short-period spectral ordinate would have a long enough period to avoid problems associated with both f_{max} and high-frequency record-processing errors, yet have a short enough period to adequately represent the observed peak in the pseudoabsolute acceleration (PSAA) response spectrum. According to spectral attenuation relationships developed by Joyner and Fumal (1985) and Campbell (1988a), this could be accomplished with a spectral ordinate having a period in the range of about 0.1 to 0.4 sec.

Similarly, the intermediate-period spectral ordinate would have a period that adequately represents the observed peak in the PSRV response spectrum. According to attenuation relationships developed by Joyner and Fumal (1985) and Campbell (1988a), this could be accomplished with a spectral ordinate having a period in the range of about 0.7 to 2.0 sec. Studies by Campbell (1988a) suggest that it would be additionally desirable to restrict the period of this ordinate to 1.5 sec or less, since it is at this period that he has found PSRV spectra to become dependent on sediment depth.

A uniform hazard spectrum would be constructed from probabilistic estimates of these two spectral ordinates using a technique similar to that proposed by Newmark and Hall (1982). This would require drawing two straight-line segments on a tripartite plot of PSRV versus period. The segment associated with the short-period peak would be drawn to pass through the short-period spectral ordinate and define a line of constant spectral acceleration; the segment associated with the intermediate-period peak would be drawn to pass through the intermediate-period spectral ordinate and define a line of constant spectral velocity.

Bill Joyner (personal communication, 1988) has also suggested that a reasonable design response spectrum for building-code applications could be constructed from two spectral ordinates: one with a period of about 0.2 sec to represent short periods and another with a period of about 1.0 sec to intermediate periods. Both of these spectral ordinates fall within the period bands suggested above. However, since the peaks in the PSAA and PSRV spectra tend to shift somewhat with respect to magnitude, distance, and site conditions, it may be more desirable to use an average of several spectral ordinates over each period band of interest, rather than rely on only two discrete spectral ordinates to define the spectrum.

Most of the disadvantages associated with this technique appear to be easily mitigated. For example, seismic hazard maps for peak acceleration and peak velocity could be developed along with those for spectral ordinates to provide a means of comparing the new seismic hazard maps with those developed previously. Furthermore, there are at least five spectral attenuation relationships currently available for Western North America (Joyner and Boore, 1988; Donovan, 1989), and it is likely that even more will be available by the time the seismic hazard maps are finalized. If the simplistic shape of a Newmark-Hall spectrum is not acceptable to the engineering or seismological communities, it would be simple to expand this technique to include more than two spectral ordinates. However, the use of additional spectral ordinates would require additional maps, as well as a more sophisticated method for constructing a design response spectrum, and should be avoided if at all possible. It may, however, be desirable to modify the proposed spectrum at short and long periods to better simulate a true response spectrum. Whether this is needed will depend on the amount of conservatism desired at these periods.

Selection of Attenuation Relationships

Regardless of which ground-motion parameters are mapped or which techniques are used to develop the design response spectrum, at least one attenuation relationship will be needed. Many criteria have been proposed for selecting appropriate attenuation relationships for specific applications. One of the more controversial issues is the choice of an appropriate functional form—especially whether this form should include magnitude-dependent attenuation (referred to as saturation). Specific selection criteria will not be discussed here, but the reader is referred to papers by Idriss (1978), Boore and Joyner (1982), Campbell (1985), and Joyner and Boore (1988) for an in-depth discussion of relevant issues and a summary of available relationships.

There are several specific issues regarding the choice of an attenuation relationship for building-code applications that have not been sufficiently discussed in the literature. One relates to the type of site condition that the relationship should represent. There is a precedent for making probabilistic estimates of ground motion for rock (e.g., Algermissen and Perkins, 1976; Algermissen *et al.*, 1982). However, since only a small fraction of the existing strong-motion data base has been recorded on rock, such attenuation relationships are not as reliable or as widely available as those for soil. Therefore, it would be better to use soil as the reference site, then adjust estimates of ground motion for other site conditions as necessary. The map itself could represent any desired site condition by simply mapping the appropriately adjusted ground-motion parameter.

A second issue regarding the selection of an attenuation relationship is the level of peer review that the relationship has undergone. In order to satisfy both engineers and seismologists, attenuation relationships commonly used by both groups should be considered. Such relationships, simply by their extensive use, will have been subjected to *de facto* peer review, regardless of their level of documentation. The appropriateness of new attenuation relationships will have to be assessed as they become available.

The last issue regarding the selection of an attenuation relationship is the potential use of multiple relationships. Neville Donovan (personal communication, 1988) has suggested that, since a building code represents a consensus opinion, an average of several attenuation relationships—a so-called consensus attenuation relationship—should be used to estimate ground motion. Although such an approach would seem to be a reasonable solution to what could otherwise be a highly controversial issue, it raises some important questions. For example, how will the uncertainty associated with differences between relationships be treated, and how will an appropriate standard error be chosen?

Regional Attenuation

Regional differences in the rate of ground-motion attenuation can easily be taken into account by adopting different coefficients of anelastic attenuation throughout the country, since most attenuation relationships include a term for anelastic attenuation in their functional forms. Although somewhat controversial, recent studies have indicated that it might also be necessary to account for regional differences in source scaling relations, stress drop, and crustal structure in the prediction of ground motion (e.g., see Campbell, 1989). Such effects are not easily incorporated by existing attenuation relationships.

Theoretical attenuation relationships are probably the most straightforward way of incorporating regional differences in scaling relations, stress drop, and crustal structure. Several such relationships have already been developed by the seismological community for use in the Eastern United States (e.g., see Joyner and Boore, 1988). However, California engineers have not found a need for such models and continue to rely on empirical attenuation relationships to estimate ground motion. As an alternative, empirical relationships could be modified to include the desired source and path effects by incorporating the results of theoretical models. Such an approach may be more acceptable to the engineering community, if the inclusion of such effects are warranted.

Site Coefficients

The 1988 edition of the UBC divides sites into four categories for purposes of defining site coefficients: rock and stiff soils, deep cohesionless or stiff clay soils, soft to medium clays and sands, and deep soft clay. The first three categories were originally proposed over a decade ago and have been adopted virtually unchanged in the current edition of the UBC. In light of the large number of strong-motion recordings that have become available during the last decade, it would seem that the time has come for these site categories to be reevaluated. Rock and stiff soils is one example of a category that might need modification. Campbell (1986) has shown that both peak velocity and intermediate- to long-period spectral ordinates exhibit substantially different amplitudes depending on whether they were recorded on hard rock or soft rock.

It may also be necessary to include additional site categories to represent site conditions more typical of regions outside of California. For example, shallow soils (high velocity-impedance sites)—a predominant site type in Eastern North America—have been found to significantly amplify both peak acceleration and short-period spectral ordinates (Campbell, 1988b, 1989). In addition, Salt Lake Valley, one of the more populated areas in Utah, has been observed to exhibit substantially higher site response than the Los Angeles Basin at all frequencies of engineering interest (Campbell, 1987b).

Recommendations

Since it is highly desirable to keep the development of response spectra for building-code applications as simple as possible, I recommend that a Newmark-Hall approach be used to develop a design response spectrum from two probabilistic response spectral ordinates. The use of two spectral ordinates rather than peak acceleration and peak velocity avoids problems regarding the effect of frequency bandwidth (f_{max}) and observed differences in the magnitude and distance scaling characteristics of peak ground-motion parameters and response spectral ordinates.

The two response spectral ordinates should be carefully chosen to characterize the peaks in the short-period and intermediate-period bands of the spectra. Consistent with the scaling characteristics of PSRV and PSAA observed by Joyner and Fumal (1985) and Campbell (1988a), the short-period ordinate should have a period in the range 0.1–0.4 sec and the intermediate-period ordinate should have a period in the range 0.7–1.5 sec. Since the peaks associated with these spectral bands tend to vary somewhat with magnitude, distance, and site conditions, an average of several spectral ordinates within each band would seem to be an appropriate means of characterizing the design response spectrum.

Attenuation relationships used to predict the spectral ordinates should be chosen according to guidelines presented by Boore and Joyner (1982) and Campbell (1985). The selected relationships should be subjected to peer review and be acceptable to both the engineering and seismological communities. The reference site for the ground-motion predictions should be soil, the predominant site condition in the strong-motion data base. Appropriate site coefficients should be used to modify these predictions for other site categories (e.g., rock) as required.

Site categories used to define site coefficients in the 1988 edition of the UBC are at least a decade old and should be reevaluated. It may be necessary to divide the current category containing rock into two categories, one for soft rock and one for hard rock. Furthermore, it may be necessary to define at least two additional site categories, one for shallow soils common to Eastern North America and one for sedimentary basins such as the Salt Lake Valley that exhibit higher site response than sedimentary basins in California.

For continuity, it would be desirable to use the same consensus attenuation relationship throughout the United States. This relationship could be developed from either theoretical relationships, empirical relationships, or both. Regional differences in ground motion (e.g., crustal attenuation, source scaling relations, stress drop, or crustal structure) could be accommodated by appropriately modifying this consensus attenuation relationship.

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How Should the Effect of Geological Site Condition Be Represented on Probabilistic Ground Motion Hazard Maps?

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Peak ground motions on soft sediments may be amplified by as much as a factor of 3 or 4. On a probabilistic ground motion map, this increase in ground motion is comparable to that obtained on rock in a region where the seismicity is increased by factors ranging from 5 to 25. Spectral ground motion amplifications up to 12 have been observed. Clearly, the effect of geologic site condition may be one of the most important contributors to ground motion hazard, and, as such, should be appropriately represented on national hazard maps, if possible, or at least represented as site factors in codes.

Although it is desirable to represent the effect of geological site conditions on national hazard maps, the method by which it is done is subject to several practical considerations. How many site conditions can be characterized by the existing suite of strong motion records? How many maps will be needed? How can the maps be usefully incorporated into a national building code? This presentation lists some of the considerations needed in coming to a conclusion about the best method of presentation.

1. *Geological site conditions change over a distance which is too small to be feasibly mapped at a national scale.*

   A map which combine the effects of seismicity rate and geological site condition is difficult to interpret. In assessing the reasonableness of the map, the user is faced with the problem of wondering whether the high hazard at a particular site is due to high seismicity or high site amplification. Hence, to map the effect of geological site condition on probabilistic ground motion, it is desirable for each map to represent the hazard for the hypothesized existence of the same condition at every site—that is, *there should be one national map for each site condition.* In this way, the variations on each map will be due only to the seismicity model. Map-to-map variations will be due only to geological site condition. To decide which map to apply to a given building location, a user would consult a local geological map at a suitable scale or obtain advice from state or local geologists.

2. *Various geological site conditions produce different site effects depending on the frequency of ground motion considered.*

   For example, shallow soils may produce amplifications or resonances for high-frequency ground motions, but be transparent to longer-period ground motions. Deeper alluvium may be transparent to high-frequency ground motion, but amplify longer period ground motions, and may develop resonance behavior for ground motions having periods close to the natural period of the site soil column. Very deep alluvium may produce resonances for even longer period ground motion, but attenuate high-frequency ground motion.

3. The predominant periods of peak ground motions increase with both magnitude and distance. Therefore, the effect noted in (2) would lead us to expect that *the geological*

site amplification effect for peak ground motions would be a function of both magnitude and distance.

Thus, we would expect peak ground motions from earthquakes of any given magnitude to attenuate differently on one site condition than on another, and we would need a different set of attenuation functions for each site condition to be represented on a map for each peak ground motion parameter to be considered. Suppose, for instance, we were to map peak velocities and peak accelerations for three different site conditions. This would require $2 \times 3 = 6$ maps for each exposure/probability level to be mapped.

Obtaining reliable magnitude- and distance-dependent attenuation functions for various site conditions requires good data at all magnitude and distance ranges for all selected site conditions. Such data do not exist in sufficient quantity and ranges to permit confident establishment of the required attenuation functions except for alluvium sites. This fact suggests that if peak ground motions are to be mapped, it is infeasible to express the expected geological site effects on such maps. Rather, we would be reduced to imposing site factors or anchoring site-dependent spectra on peak acceleration, as is done in current codes. Such measures are poor approximations to probabilistic site effects.

4. On the other hand, because the site effect is primarily frequency dependent, *if we used "band-limited" ground motion parameters, like response velocities for various periods, the site effect for a given parameter is likely to be approximately constant, regardless of magnitude and distance.*

   Whereas for peak ground motion we would require an attenuation function for each site condition for each parameter to produce separate maps, all we would need for each band-limited ground motion parameter is just one attenuation function, to produce a single map, and a set of correction factors, one for each geological site condition. (We might prefer maps of more than one parameter in order to provide a better sense of the shape of a uniform hazard spectrum.)

   Inasmuch as the band-limited parameter site factors would not be dependent on distance and magnitude, good data at all magnitude and distance ranges is required only for a basic, reference, site condition. For all other site conditions, a relatively sparse distribution of data would be sufficient to define the needed site factor.

5. *The limited amount of geologic site condition data available for strong-motion stations may mean that only a few, very generalized, site conditions can be defined.*

   Considering the United States as a whole, there must be a very large number and variety of geologic site conditions. The sites of strong motion recordings may not represent many of these sites, when considered in detail. Even when generalized to many fewer "typical" conditions, it may not be possible to assure that strong-motion site conditions will represent those of the rest of the U.S. Likewise, the more generalized are the site conditions, the less likely it is that any single site condition can represent the extremes in the possible site effects. Thus, it may be necessary to provide additonal means, perhaps through special code provisions, to suggest the possible extremes in hazard for non-typical sites.

Although national hazard maps in the past have represented probabilistic ground motion on "rock" (really, "firm ground"), the predominant site condition for available strong motion recordings is moderate-to-deep alluvium. A few rock-site recordings are available, but the behavior of high frequency ground motion on these sites is very variable. Thus, the geologic site condition for which the most accurate attenuation function can be determined is moderate-to-deep alluvium. Therefore, in order to make the basic map represent a rock site condition, the alluvium attenuation function will have to be corrected, via the site factor, to rock.

However, in view of the sparsity of the rock stations and the high variability of their site effect at high frequencies, this rock site factor is very likely to change with the recording of new data. Hence, the choice of a rock site map as the basic map incurs the penalty of making the maps easily outmoded by the determination of better rock-to-alluvium site factors. A more stable basic map would be one for the moderate-to-deep alluvium site condition; new data would result in a change of the site factors rather than of the basic map. Such a choice, however, might be considered undesirable, for failing to provide continuity with past practice.

6. *An important goal is the capacity of the hazard maps to establish the changes in design spectral shape according to site condition.* Such a spectral shape could be defined by points obtained from several maps, representing the effects at several spectral ordinates, or a previously-designed shape could be anchored to an ordinate obtained from a single map.

   With moderately good data it should be possible to define uniform hazard spectra (UHS) over a useful range of frequencies. Practical considerations limit the detail possible—the need to limit the number of maps and the limited number of typical site conditions for which the data will permit the definition of site factors. Hence, it may be impractical to fully characterize site-specific spectral shape from mapped values. Furthermore, it is sometimes argued that the use of a uniform hazard spectrum would be undesirable, inasmuch as such a spectrum at a given probability level does not represent a realistic spectrum for any given single earthquake. (That is, a UHS is suitable for designs using only a single period, as with a single-degree-of-freedom system. For modal design, in which ordinates for several periods are desired, the UHS ordinates may be governed by smaller magnitude earthquakes for short periods but larger magnitude earthquakes for the longer periods. Thus the result does not represent a realistic single-earthquake demand for the structure.)

   The advantage of the uniform hazard spectrum is that it represents a multiple earthquake demand for single degree of freedom structures. The UHS at various sites will change because of the differing configuration, seismicity rates, and maximum magnitudes in the vicinity of the sites. Thus, the UHS provides great precision in the description of the spatial variation of hazard. The question is whether the code agencies wish to give up this precision in order to provide more realistic spectra for design earthquakes.

Thus, alternatively, the probabilistic ground motion maps could be used to provide values on which to anchor spectra whose shapes have been determined external to the hazard-map process, possibly by code agencies. For broader applicability, the spectral shape to be applied could be designed to be a function of the level of the anchoring probabilistic ground motion. The same strong-motion data to be used for the development of attenuation functions may give useful guidance for real earthquake spectral shapes for specific site conditions, magnitudes, and distances.

It is important to get this spectral shape "right," and it is not clear how an acceptable shape is to be defined. For conservatism one might choose to use a spectrum which envelopes those considered most relevant. However, the resulting spectrum will not only have a different exceedance probability at each frequency, but also may not correspond to a realistic single earthquake.

Although it is common to anchor spectral shapes to peak accelerations, more control over the design shape may be possible if the spectra were anchored to the value at one or more response periods. This would avoid a problem arising from the increase in peak acceleration expected in the eastern United States due to the increased amount of high-frequency energy in the recorded ground motion ("higher f_{max}").

7. *Although one of the most damaging effects due to site condition is "tuning" between the resonance period of the soil column and the natural period of structures at the site, mapping of this hazard depends upon knowledge of existing building periods and site conditions in urban areas.* It may not yet be feasible to map the existence of this hazard.

   Although this effect may be rare in terms of susceptible area and number of buildings involved, the effects are so catastrophic and the life loss so high that it is desirable to make a concerted effort to mitigate this hazard. Examples are the 1967 Caracas earthquake and the 1985 Mexico City earthquake. The methods sketched above provide information which can be used to assist in site specific planning for new buildings, for which resonance can be avoided.

   However, for existing buildings it is not clear how this effect can be taken into account on hazard maps, without knowledge of the periods of existing buildings and the detailed knowledge of urban site conditions. It may be possible to produce auxiliary regional maps on which are indicated site conditions which could produce resonance over certain period bands, for certain types of structures which are known to exist, but a proper geologic inventory may not be available for this next generation of hazard maps. Concern for hazard to existing buildings may go beyond the intention of the codes for which the hazard maps are intended. Also, concern for local areas of hazard may be the proper responsibility of local agencies rather than those agencies which produce national codes.

DETERMINATION OF THE ENGINEERING CHARACTERISTICS OF EARTHQUAKE GROUND MOTIONS

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Determination of the engineering characteristics of earthquake ground motions is a complex task since they depend on so many factors including:

1. The magnitudes of earthquakes which may occur on various seismic sources
2. The distances of potential seismic sources from any specific location
3. The local soil conditions at any given location
4. The travel path geology for seismic waves
5. The source mechanisms of the earthquakes which may occur

and 6. Directivity effects.

Not all of these effects are readily quantifiable at the present time but they all influence the characteristics of the resulting ground motions.

Local soil conditions alone can clearly have a major effect on the characteristics of earthquake motions. This has been recognized for many years and it has recently been demonstrated again by the dramatic differences in ground motions which occurred in different parts of Mexico City in the Mexico earthquake of September 19, 1985. There is clear evidence that local soil conditions can either amplify or attenuate earthquake ground motions and can have a major effect on many significant characteristics of earthquake motions including peak ground accelerations, peak ground velocities, frequency characteristics of surface motions, and the forms of response spectra for surface motions.

Other factors listed above may also affect the motions. It is well known that the frequency characteristics of motions in a single geologic formation, rock, are influenced significantly by the distance of a site from a seismic source and there is good reason to believe that peak accelerations from slippage during strike-slip faulting is likely to be lower than those resulting from thrust or reverse faulting.

Because of the unknown or uncertain effects of all of these variables, many of them must be allowed for by a probabilistic interpretation of available empirical data in addition to all of the uncertainties in seismic hazard evaluations introduced by the unknown sources and frequencies of earthquake occurrences. For many purposes, therefore, probabilistic evaluations are a necessary feature of the development of seismic hazard maps.

Despite the use of this approach, however, the complexity of the problems associated with making useful earthquake hazard evaluations seems to raise serious doubts about the extent to which useful information can be presented in large-scale earthquake hazard maps. To cover all relevant aspects in a meaningful way, even on matters related only to local soil conditions, would require such a large number of maps that the task would become prohibitive or even if it were accomplished, would involve such a large number of maps that the value of the results would be seriously diminished.

In view of this it might well be desirable to limit the parameters described in hazard maps, but to select and present them in such a way that engineers and earth scientists can use them as a base from which to determine other characteristics of ground motion that would be useful for engineering design purposes. With this thought in mind, useful parameters for presentation on future maps might include simply probabilistic assessments of

1. Peak ground accelerations on rock from local earthquake sources (say closer than about 50 kms).
2. Peak ground accelerations on rock from distant earthquake sources (say greater than 100 kms).
3. Peak velocities on rock from local earthquake sources (say closer than 50 kms).
4. Peak velocities on rock from distant earthquake sources (say greater than 100 kms).

With this information in hand, engineers could then extrapolate the information to develop useful information (response spectra) for design purposes using available knowledge of site-specific effects relating rock motions to those for sites underlain by other soil types and with some allowance for other factors whose effects on ground motions can be clearly identified.

This concept is offered only as a basis for discussion at the present workshop and is not intended as a firm recommendation on the direction which earthquake motion mapping should necessarily take in the development of a new generation of maps. That conclusion can only result from a consideration of all views expressed by all participants in the proceedings of workshops such as this.

A NEW GENERATION OF PROBABILISTIC GROUND-MOTION HAZARD MAPS: SEISMIC SOURCE ZONES REVISITED

by
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Goal and Principles: A primary goal in the reevaluation of national seismic source zones is to incorporate new understanding of earthquake sources, their recurrence rates and their maximum magnitudes. However, untested hypotheses about sources and processes of earthquake generation should be avoided in a map for code-development purposes. Sensitivity studies will illustrate the consequences (in terms of ground motion) of speculative hypotheses to indicate the range of ground motions resulting from uncertain earthquake sources and their seismic characterization (e.g., Thenhaus and others, 1987). To accomplish the goal of incorporating new understanding, we must examine and assess information developed in the past ten years by region, especially focusing on new understanding of seismogenic structures. Where data are ample and the seismogenic structures accessible as in the western United States, advances in understanding have come more frequently than where data are few and causal structures are obscure or inaccessible as in the East. This difference between East and West requires different approaches to seismic source zones in order to best use the available information.

The principles on which the 1982 source zones were based (Thenhaus, 1983) remain valid for representing the various degrees of certainty with which earthquakes can be associated with causal structures. These are zoning on: (1) locations of individual faults or areal extent of faulting where faults are mapped as having geologically young displacements or have a recognized association with seismicity, (2) regional structural style where seismicity is associated with distinctive structural settings, and (3) regional distribution of seismicity where causal structures are not known.

Advances and Insights: There have been significant advances in understanding regional tectonics since national seismic source zones were depicted some ten years ago. Some examples are: (1) recognition of active fold systems neighboring the San Andreas fault, as demonstrated in the eastern Coast Ranges by the 1983 Coalinga, California, earthquake ($M_L = 6.7$) (Stein and King, 1984) and within the Los Angeles basin by the 1987 Whittier Narrows earthquake ($M_L = 5.9$) (Jones and Hauksson, 1988); (2) revolutionary concepts of the structural history and structure of the Appalachians derived from deep-crustal reflection profiling studies (e.g., Cook and others, 1979) and models of terrane accretion (e.g., Williams and Hatcher, 1982); (3) recognition of the possibility of a great earthquake on the shallow plate interface of the Cascadia subduction zone beneath the Pacific Northwest (Heaton and Kanamori, 1984); (4) reconfirmation of the significance of Holocene faulting in general by the 1983 Borah Peak, Idaho, earthquake ($M_s = 7.3$) on the Lost River fault, which had Holocene movement but no historical seismicity prior to 1983 (Crone and others, 1987); (5) recognition of Holocene rupture on the Meers fault in south-central Oklahoma (Gilbert, 1983).

The concepts of fault segmentation and repeated characteristic-size earthquakes on individual fault segments are improving our understanding of fault behavior. Some local geologic features of fault zones are recognized as the long-term structural consequences of the repeated stopping or starting of large ruptures. Such geologic features are fault-rupture barriers and are becoming increasingly important in paleoseismic reconstruction of a fault's rupture history. Thus, seismological and geological concepts are merging into clearer models of the long-term behavior of some fault zones. Along the San Andreas, Hayward, and San Jacinto faults, the geologic evidence of segmentation combined with the historical earthquake record and paleoseismological evidence has recently allowed the calculation of conditional probability estimates for large earthquake occurrence in future time windows of 5 to 30 years (Working Group on California Earthquake Probabilities, 1988).

New Generation of Source Zone Maps: While the goal and principles of the new maps will be the same as the 1982 maps (Algermissen and others, 1982; Thenhaus, 1983), we anticipate improvements in the details of source zone definition. For example, in the eastern United States, source zones defined on the historical distribution of seismicity will be distinct from regional background zones defined by geologic structure and geologic history (Wheeler and Thenhaus, this volume). Separation of the seismological and geological bases will allow source zone boundaries to be defined more objectively than previously. Small zones based on the inferred presence of hypothetical active faults will be avoided.

In the West, some large faults (as the Wasatch and San Andreas) were explicitly represented in the 1982 source zone map and modeled as linear sources for large earthquakes. This explicit modeling lays the foundation for illustrating the ground-motion consequences of fault-specific segmentation models. Detailed segmentation models would best be illustrated in larger-scale maps, separate from the 1:5 million-scale national map, to properly illustrate the distribution of higher ground motions near the fault traces. More appropriate for the national scale might be random rupture models along the faults using average recurrence intervals for large earthquakes as determined from recent paleoseismic investigations, but constraining the ruptures to lengths appropriate for the segmentation model. Aggregated seismic rates are more robust than rates associated with individual segments.

Ground-motion consequences of time-dependent models of earthquake occurrence will also be investigated. The Working Group on California Earthquake Probabilities (1988) calculated time-dependent conditional probabilities for large earthquake occurrence on the Hayward, San Jacinto, and San Andreas faults at future time intervals between 5 to 30 years. Additional calculations will be necessary to establish the conditional probabilities for the next 50-year period for comparison to the national hazard map. The main point is that our approach to individual fault models will be to illustrate the consequences of different models, ranging from the robust to the more speculative or still poorly constrained.

We have refined the geological bases of regional source zones in the Great Basin province (Thenhaus and Barnhard, 1988; submitted). While knowledge continues to grow regarding the ages and locations of Quaternary faulting events in the province, boundaries to regional source zones have been defined largely on subjective bases in lieu of a regional tectonic framework for young faulting. Three transverse structural zones that cross the province segment and terminate generally north-trending belts of Quaternary faulting. These transverse zones appear to be fundamental elements in the regional tectonic framework of young faulting throughout the province. One important insight is the identification of the Sonoma Range Seismic Gap north of the 1915 Pleasant Valley surface ruptures in west-central Nevada (Thenhaus and Barnhard, 1988). Future earthquake rupture on the Sonoma Range fault would complete a belt of historic faulting along the northern half of the Central Nevada Seismic Zone.

Elsewhere in the western U.S. we anticipate generally minor alterations to most source zones after taking into account new information. However, one significant change will be a redefinition of zones in the northern Basin and Range province, north of the Snake River Plain in Idaho, using paleoseismological data and structural models developed following the 1983 Borah Peak earthquake.

In-house improvements in data handling and modeling will benefit the accuracy of seismotectonic models and the representation of location uncertainty in source zone boundaries (Bender and Perkins, 1987; Bender, 1986). The acquisition and development of digital fault data bases for California, Nevada and Utah will increase the accuracy of modeled fault locations and will particularly benefit the production of larger-scale maps. The ability to model dipping, planar ruptures in the updated computer code (Bender and Perkins, 1987) will improve the modeling of the Juan de Fuca-North American plate interface in the Cascadia subduction zone of the Pacific Northwest.

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SOURCE ZONES AND EARTHQUAKE RATES IN THE EAST

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Introduction

East of the Rocky Mountains seismicity is sparse and most active faults are not exposed at the surface. Accordingly, relations between seismicity and geology are more ambiguous in the East than in the West. This fundamental difference between the regions has caused two problems in defining eastern source zones for earlier hazard assessments.

First, in general it has been difficult to combine geology and seismicity in the East to define source zones in a clear, logical way. The few exceptions to this difficulty are zones with abundant seismicity that has clear spatial associations with particular groups of faults, as is the case at the Reelfoot and St. Lawrence rifts and the Charlevoix impact structure.

Second, source zonation has depended on changable hypotheses about the geological causes of eastern seismicity. If source zones change, the ground-motion maps based on them also change (e.g., Thenhaus and others, 1987). But hypotheses rise and fall, so it is not always clear at the time whether a change is an improvement or an error. Examples of changing hypotheses are the controversies over the Ramapo fault (contrast Aggarwal and Sykes, 1978, with Ratcliffe, 1981, 1982) and the Atlantic Coast stress province (contrast Zoback and Zoback, 1980, with Zoback and others, 1985).

We propose to attack both problems in the East as we update the source zones from the 1982 probabilistic maps of Algermissen and others (1982). (For our proposed treatment of western source zones, see Thenhaus and Wheeler, this volume.) We will treat eastern geology and eastern seismicity separately. We propose to define two kinds of source zones--geologic source zones based on geologic and geophysical information and seismicity source zones based on spatial concentrations of earthquakes.

Geologic Source Zones

Most large intraplate earthquakes are conjectured to nucleate in the lower part of the brittle upper crust (e.g., Scholz, 1988). We propose to use regional geologic structure of the brittle upper crust to define a few (perhaps 5-10) large geologic source zones that we conjecture to produce infrequent, scattered earthquakes that usually are hard to associate with any previously-recognized fault. We will distinguish these geologic source zones by their tectonic styles and histories, their crustal ages and thicknesses, and related geological and geophysical properties. We assume that these regional differences in tectonic and crustal properties determine most regional differences in seismic activity rates and maximum magnitudes.

For example, recent geological and geophysical results allow the Appalachians and eastern seaboard to be divided into two long, parallel, geologic source zones. The two zones lie between ancient North American continental crust on the northwest and young Atlantic oceanic crust on the southeast. The northwestern zone is the realm of abundant normal faults that formed as the Atlantic's predecessor ocean (Iapetus) first opened 734-570 million years ago. These faults are at seismogenic depths, masked by overlying Appalachian thrust sheets. In southwestern Virginia and eastern Tennessee such faults appear to be undergoing seismic reactivation in the modern compressional stress field. In contrast, the southeastern zone comprises diverse crust complexly deformed by Iapetan extension, Appalachian compression and metamorphism, and Mesozoic extension. The northwestern and southeastern zones have different kinds of faults with different strengths and geometries, so seismic reactivation of the faults is also likely to differ in frequency and earthquake magnitude between the zones.

The geologic source zones will differ from the background source zones that are common in probabilistic hazard analyses. Often background zones are made up of areas that are left over after other source zones are defined, whereas our geologic source zones will be defined independently of other kinds of zones. The geologic source zones include the tectonic and background types of source zones of Johnston (1987). Because eastern seismicity is sparse, estimation of the seismicity rates and maximum magnitudes of geologic source zones will be aided by analogies to geologically similar areas world-wide (Coppersmith and others, 1987a, b).

Seismicity Source Zones and Seismogenic Source Zones

Within the large geologic source zones concentrations of historical seismicity will be used to identify localized areas of comparatively more frequent earthquakes. We call these areas seismicity source zones (seismicity zones of Thenhaus, 1986; seismic source zones of Johnston, 1987). A seismicity source zone will have the same maximum magnitude as the surrounding geologic source zone but will have a greater area-normalized rate of seismicity. The purpose of the seismicity zones is to preserve the influence of historical earthquake concentrations on the ground-motion hazard maps (e.g., Thenhaus and others, 1987).

A few seismicity concentrations correspond to known geologic structures, such as the Reelfoot and St. Lawrence rifts, so we could represent these concentrations as source zones with fuzzy boundaries (Bender, 1986). These few source zones would be based on both geology and seismicity. We call them seismogenic source zones (Thenhaus, 1986; seismotectonic source zones of Johnston, 1987).

Subjectivity and Uncertainty

Seismicity of a concentration can be smoothed geographically and by magnitude to represent uncertainty about seismogenic processes and about locations of future related seismicity (Perkins and Algermissen, 1987). Geographic smoothing and magnitude smoothing will involve some subjective choices. However, because geology and seismicity will be treated separately for most source zones, each choice and its supporting arguments can be described separately, and the consequences of each choice and its alternatives can be expressed quantitatively (e.g., Perkins and Algermissen, 1987). The result will be a clear characterization of the subjectivity and its effects.

The uncertain relations between eastern geology and eastern seismicity produce uncertainty in the estimated hazard (Bernreuter and others, 1985; Risk Engineering, Inc., and others, 1986; Thenhaus and others, 1987; Algermissen, this volume). Simply put, uncertainty about the geologic causes of most eastern seismicity is too large for us to draw small eastern source zones with much confidence, except in unusually active areas like the upper Mississippi embayment and part of the St. Lawrence River valley. Where present understanding cannot choose between competing seismotectonic models we will illustrate the hazard that results from each model. Hazard assessments for different purposes might require different characterizations of the hazard (Algermissen, this volume). For example, applications such as building codes for non-critical structures might require the model that produces the best estimate of the hazard, whereas applications such as emergency planning might require the model that produces the highest reasonable hazard.

Conclusions

Our proposed separation of eastern geology and eastern seismicity into different kinds of source zones will provide three advantages.

(1) We will define eastern source zones with an approach tailored for the East. We will use an approach derived from the geological and seismological characteristics of the East, but compatible with the western approach that combines geology and seismicity to define source zones.

(2) We will define eastern source zones clearly and logically by explicitly separating geology and seismicity.

(3) We expect that our source zones will change less with time than have previous sets of eastern source zones. The large eastern geologic source zones will be unlikely to change much as hypotheses come and go because the zones will be based on widely accepted regional geologic characteristics. Similarly, the seismicity source zones will not change much with changing hypotheses because the concentrations are based on observations, not inferences.

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LONG RANGE EARTHQUAKE PROBABILITIES AND INSURANCE INDUSTRY NEEDS

by
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The probability of a large earthquake affecting a major metropolitan area of western California in the next 30 years is high. The Working Group on California Earthquake Probabilities (1988) estimates a 0.6 probability of a major earthquake in the next 30 years along the southern San Andreas fault, east of Los Angeles. In that same time period, the San Francisco Bay area has a 0.5 probability of experiencing a major earthquake. Such earthquake forecasts derive from new approaches to the questions of where and when will large earthquakes strike.

The basic concept of earthquake recurrence is one of cyclic stress accumulation and release along faults. Long faults as the San Andreas in western California do not rupture their entire length in large earthquakes but rather, rupture in discrete segments of varying length depending, in general, on the magnitude of the earthquake. Accumulation of stresses along faults in coastal and western California result from differential movement between the Pacific and North American plates that occurs at a rate of centimeters per year and has persisted over a geologic time scale of millions of years. Ground displacements across fault segments in large earthquakes is on the order of meters. In general then, recurrences of large earthquakes along individual segments of faults is on the order of 100 to several hundred years. By the same reasoning, the expected repeat time of the segment-rupturing earthquake can be calculated if both the long-term average annual rate of slip on a fault segment and the amount of slip in the last segment-rupturing earthquake are known. As time since the last earthquake increases, so too does the probabililty of occurrence of the next earthquake. Thereby, calculation of probabilities of large-earthquake occurrence during future time frames is possible.

In response to a National Earthquake Prediction Evaluation Council recommendation that the probability of occurrence of large ($M \geq 7.0$) earthquakes in California be evaluated, the USGS established the Working Group on California Earthquake Probabilities. The results of their initial evaluations and deliberations were recently released as USGS Open-File Report 88-398. Figures 1a-b are from that report and summarize the conditional probabilities for large earthquake occurrence between the years 1988-2018 developed for fault segments of the San Andreas, San Jacinto and Hayward faults of western California. The "conditional" aspect of these probabilities is that the large earthquake has not yet occurred within the thirty year time window. Immediately following an earthquake on a given segment, the associated conditional probability drops to zero, then increases as a function of time. Total probabilities for three regions of western California, developed by aggregating probabilities for individual segments, are summarized in Table 1 for time periods of 5 through 30 years. The probability of a large earthquake *anywhere* along the entire length of a fault is higher than the probability for any of the fault's constituent segments for a given time period of interest. Notably, the probabilities for all three areas are significant with southern California having the highest probability of experiencing a large earthquake along the southern San Andreas fault. Moreover, the regional probability estimates should be considered minimum values because only those faults having sufficiently developed geological data for recurrence estimation are evaluated. Other faults not having sufficient data for time-dependent probability calculations are not addressed although they too contribute fractionally to the total probability of the given regions experiencing a large earthquake in the given time frames.

Other regions of western California, not in close proximity to the large strike-slip faults discussed above, are subject to major earthquakes from faults or fault systems that are presently only poorly understood and the geographic locations of which are imperfectly known. West of the San Andreas fault, the Transverse Ranges typifies such a region. Some major mapped faults in this region have estimated upper-bound earthquakes of $M = 7.0$

(Morton and Yerkes, 1987). Other faults in this complex region are not mappable at the surface but still have seismic potential as illustrated by the Whittier Narrows earthquake of October 1, 1987 ($M_l = 5.9$) (see Earthquake Spectra). Faults in this region are of an oblique-thrust-type origin and are not as easily studied as the primary strike-slip faults of the San Andreas system. Nonetheless, their contribution to the long-term (i.e., 30 years) earthquake potential is considerable although not easily quantified in terms of time-dependent probabilities with presently available data.

These time-dependent probabilities for large earthquake occurrence along major faults in western California invite a probabilistic framework to discuss and assess the insurance industry needs for dollar-value estimates of Maximum Probable Loss, Average Annual Loss, and Catastrophe Potential. Certain insurance industry definitions, such as Maximum Probable Loss, appear in need of a time-frame reference to be meaningfully used in conjunction with long-range earthquake forecasts.

Ideally, insurance industry needs and definitions would seemingly best be formulated in terms of probabilistic ground motion, or ground motion spectra hazard estimates (see Algermissen, this volume, for a discussion of procedures used in establishing these estimates). Such criteria have become the standard reference for the engineering community in the earthquake resistant design of structures. Procedures for incorporating time-dependent earthquake recurrences and for accounting for uncertainty in fault location and maximum magnitudes are easily accommodated by a probabilistic ground-motion mapping procedure. Moreover, such definitions would be in accord with modern engineering criteria for earthquake resistant design of the structures that the insurance industry covers through policies. The apparent benefit would be a clearer correspondence between building design and insurance premium. Other geotechnical aspects of the seismic hazard problem such as landsliding and liquefaction are also important and should be factored into the overall estimate of the earthquake risk.

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TABLE 1.–Probability of one or more large earthquakes on faults of the San Andreas fault system.

Geographic Region or Fault	Expected Magnitude	Probability for Intervals Beginning 1/1/88			
		5 yr	10 yr	20 yr	30 yr
San Francisco Bay Area	7	0.1	0.2	0.3	0.5
Southern San Andreas Fault	7 1/2–8	0.1	0.2	0.4	0.6
San Jacinto Fault	6 1/2–7	0.1	0.2	0.3	0.5

Figure 1a.

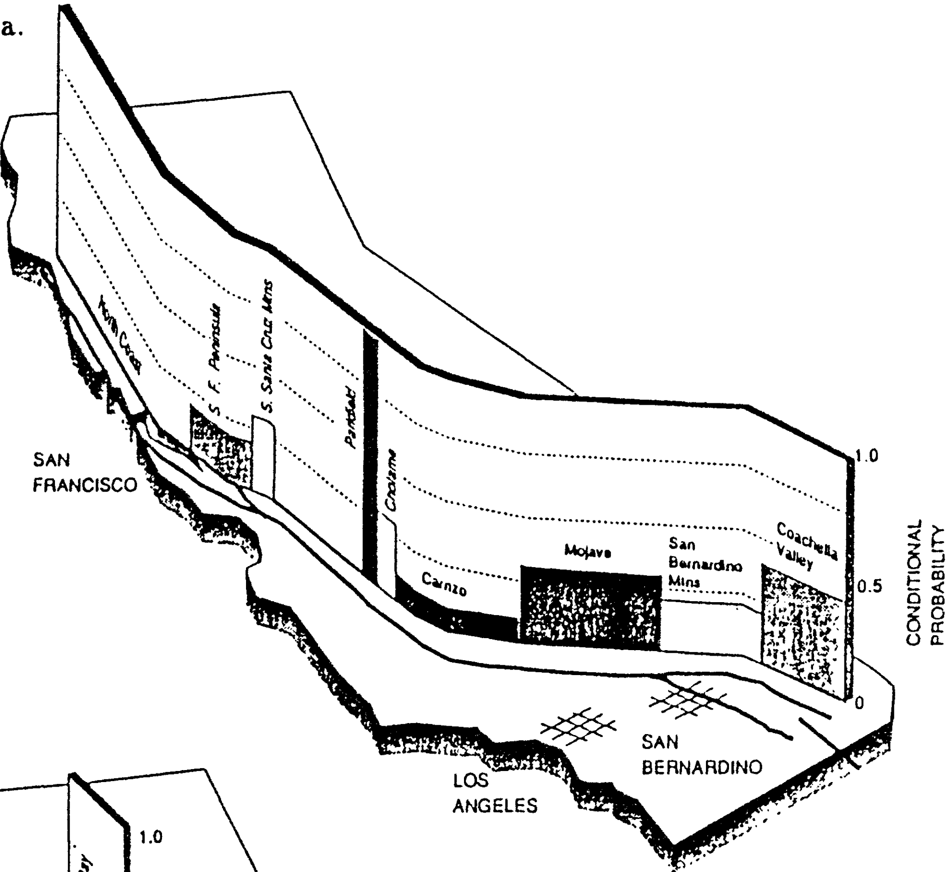

Figure 1b.

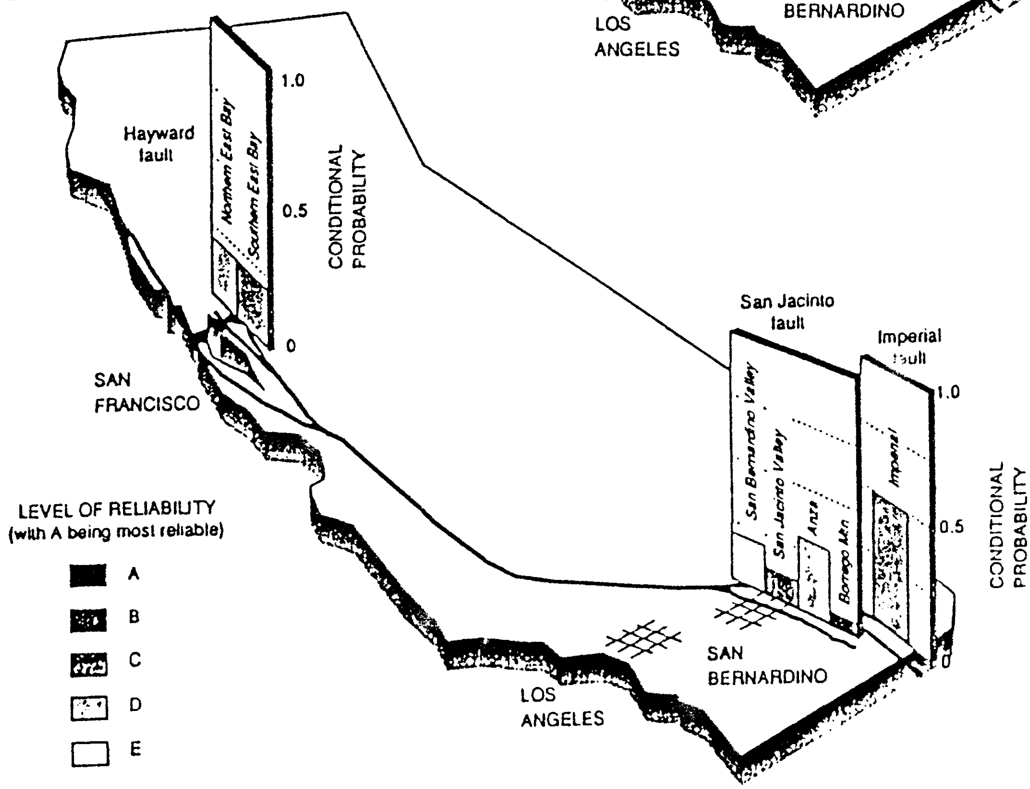

Figure 1.–Conditional probability for the occurrence of major earthquakes along the San Andreas fault (Figure 1a) and Hayward, San Jacinto, and Imperial faults (Figure 1b) in the 30-year interval from 1988 to 2018.

COMMENTS ON INPUT INTERPRETATIONS FOR PROBABILISTIC SEISMIC HAZARD

by

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The purpose of a probabilistic seismic hazard (PSH) analysis is to provide a documented basis for informed decision making about seismic safety. Accepted safety is usually achieved by satisfying code seismic design requirements that are based on PSH mapping. Mean centered estimates of PSH have usually been used; however, knowledge of the variability on hazard can have a major influence on decisions regarding cost-effective, safe seismic design requirements. Thus, quantification of uncertainty is an important component of complete PSH mapping.

Variability in PSH derives from two sources: the randomness in earthquake process inherent in any modeling approach, and uncertainty about appropriate models, particularly, model inputs (McGuire, Stepp and Toro, 1986; Toro, McGuire and Stepp, 1989). Depending on application, the appropriate seismicity model may be selected with a reasonable degree of certainty (Cornell and Winterstein, 1986). Given our current state of knowledge, however, input interpretations (seismic sources, source seismicity parameters, source maximum magnitude, appropriate lower-bound magnitude for hazard computation, seismic wave attenuation and the effects of local site geology on ground motion) remain highly uncertain. A goal of the proposed new generation of seismic hazard maps should be to quantify and incorporate this uncertainty in a format useful for engineering application.

The uncertainty contributed by a given input parameter depends on how much the PSH results vary when the parameter is varied, and on how uncertain the parameter is (McGuire, et al, 1989). Recent studies in the eastern United States have shown that uncertainty in seismic source interpretations is the greatest contributor to total PSH uncertainty. Uncertainty in seismic wave attenuation and site response, and selection of lower-bound magnitude for seismic hazard computation are shown to be lesser, but significant contributors to total PSH uncertainty. Uncertainty in the seismicity parameters (a, b) and uncertainty in maximum magnitude appear to be relatively small contributors to total PSH uncertainty (McGuire, et al, 1989). These results suggest that the planned reevaluation of the national seismic hazard maps should place strong emphasis on incorporating new understanding of earthquake tectonics and available data in an interpretative structure that captures the current state of scientific uncertainty about earthquake sources.

Uncertainty about earthquake sources has two components; 1) uncertainty about earthquake causes and processes, and 2) data uncertainty, i.e., inability to evaluate processes or resolve physical properties of tectonic features (McGuire, et al, 1989). Recent earthquakes near Saguenay, Quebec on November 25, 1988 and Whittier, California on October 1, 1987, continue to remind us that the process of tectonic strain release in the earth strain release is poorly understood. Thus, PSH mapping should incorporate recognition that earthquakes may occur on previously unmapped tectonic structure which have not shown historic earthquakes.

The Saguenay earthquake was in a continental interior tectonic environment where tectonic strain rates are low and poorly expressed (or not expressed) in the geologic data. The Whittier earthquake on the other hand, occurred in an active plate boundary tectonic environment where strain rates are high and generally expressed in faults that reach the earth's surface. Yet both of these earthquakes were a surprise in respect to their lack of association with previously known tectonic structure or historic seismicity. I believe these two examples illustrate the need to provide for alternative source interpretations based on compilations of the most complete available geological and geophysical data and using a structured approach which involves weighted alternative tectonic bases for seismic sources (McGuire, et al, 1989). The interpretation structure should provide for definition of background sources which capture sources too small to be identified in the regional scale data, i.e., sources below the resolution of regional data sets. Geographic data base systems and the availability of geophysical and geological data in digital format now permit the data to be compelled and displayed on a common scale large enough to be useful for seismic source interpretations.

Uncertainty in seismicity modeling can be significantly reduced by selecting the appropriate models for high strain rate and low strain rate tectonic regions. Winterstein and Cornell (1986) have shown the conditions urder which time-dependent models are needed. Other aspects of seismicity modeling are also important to avoid bias and to quantify uncertainty. Among these are homogenization of the earthquake catalog with respect to magnitude and multiple events, proper modeling of catalog incompleteness, and provision of the flexibility for interpreters to allow variation of seismicity rates within a seismic source (McGuire, et al, 1989).

The lower-bound magnitude used for seismic hazard computation is a significant source of uncertainty. The importance of this parameter is greater at low ground motion levels and high exceedance probabilities. A technical basis for assessing lower-bound magnitude is given by McCann and Reed (1989a, 1989b).

Recent advances in ground motion characterization (McGuire, Toro and Silva, 1988, Joyner and Boore, 1988) provide the basis to significantly reduce the uncertainty in PSH due to this input parameter. The band-limited white noise ground motion model has been shown to effectively correlate with a wide range of ground motion observations (Silva, 1989). This model, which has been extended to near source conditions (Joyner and Boore, 1989), is sufficiently well developed to be adopted for PSH modeling. The model parameters, though region-independent, are reasonably controlled by existing data (Toro, McGuire and Silva, 1988; Somerville, et al, 1986; Silva, 1989). With a reasonable effort, region-dependent ground motion estimation procedures could be developed for defined rock conditions. Uncertainty due to variability in anelastic attenuation and to stress parameters can now be reasonably quantified with existing data.

A reasonable approach would be to define base models for the continental interior and Western U. S. crustal conditions. These would be rock-based models and would account for differences in high frequency cut off in these to differing crustal regions. With a modest effort, the geologic conditions could be categorized into a manageable member that would include the range of site geology. Site response could be then be determined for each of these categories and incorporated into the PSH mapping (McGuire, Toro and Silva, 1988).

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Treatment of Parameter Uncertainty and Variability in Seismic Hazard Maps

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Introduction

Probabilistic ground-motion hazard maps are calculated using probabilistic models that reflect our uncertainty in the locations, sizes, and occurrence times of future earthquakes. Uncertainty in the locations of future earthquakes is modeled by specifying areal source zones and "source faults on which future earthquakes are assumed to be randomly distributed. Uncertainty in the sizes of these earthquakes is modeled by a distribution of earthquake rate vs magnitude, over a range defined by a minimum and maximum magnitude. Often the distribution follows the Gutenberg-Richter law, in which the logarithm of the rates and the magnitudes fit a straight line whose ordinate and slope are given by an a-value and a b-value. The earthquake occurrence times are generally modelled by exponential interoccurrence times at a constant rate, but the larger magnitudes may be assumed to occur according to a quasi-periodic law.

To produce a hazard estimate at a site, an attenuation function (i.e., a function that relates ground shaking at a site to earthquake magnitude and distance of the earthquake from the site) is used to calculate a histogram showing average annual occurrence rates of various ground-motion levels expected at the site from the modeled earthquakes. The ground-motion level that has a given probability of being exceeded (or not exceeded) at the site during a specified time interval is calculated from the annual ground-motion occurrence rates. To produce a hazard map, ground-motion estimates are obtained for each point on a grid of points, and contours of constant ground-motion levels are drawn through the resulting grid of values.

The values on the map are clearly a function of the parameters used to model the earthquake sources, the magnitude distributions, the interoccurrence time distribution, and the attenuation function selected. But these model parameters are themselves uncertain. Given the uncertainties in each of the model parameters, we would like to make a "best" estimate of probabilistic ground motion at each site, and also an estimate of the effects of the input uncertainties on the results. In the past it has been suggested that error bars be provided for the map results or that one or more extremes be mapped.

In this paper, we demonstrate that for certain model parameters, under reasonable assumptions, the probabilistic ground motion result obtained by merely doing a single calculation using a central value for each of the parameters is not significantly different from the result obtained by integrating over the uncertainty in each of the parameters. Using the assumed distributions of these parameters, error bars can be calculated for the resulting ground motions. For other modelled uncertainties, an averaged result is likely to be misleading and representation of the variability in results by error bars has no useful meaning. For these uncertainties we advocate displaying alternative results.

Sources of Uncertainty in Seismicity Parameters

Historic seismicity has generally been regarded as the best available basis for estimating future seismicity, and recorded earthquakes are typically used to estimate seismicity parameters, that is, a future earthquake rate, a *b*-value and a maximum magnitude, m_{max}, for each source. However, a number of considerations suggest that estimates based on recorded earthquakes are likely to be highly uncertain.

(a) The earthquake catalogs that are used are incomplete (the fraction of missing earthquakes tending to be higher in earlier times, and higher for smaller magnitudes).

(b) The time of the catalog may be less than the average interval between the larger earthquakes, making estimates of the frequency of larger magnitude earthquakes, and of the largest possible magnitude, m_{max}, highly unreliable.

(c) Locations of earthquakes may be inexact (even rounded to the nearest degree of half-degree) and location errors can affect the set of earthquakes included in the study.

(d) The extent of a seismically homogeneous source area is generally not well defined; changing the boundaries of an area can alter the number and magnitude distribution of the earthquakes included.

(e) Magnitudes of historic earthquakes are often not accurately known, a magnitude possibly having been estimated long after the earthquake from intensity data gleaned from newspaper accounts.

In some parts of the country where there is sufficient data, geologically-determined seismicity rates may be preferred. Nevertheless, recurrence estimates based on slip have high variability because of the uncertainty in upper-bound magnitude (or moment), the assumed extent of aseismic slip, and the *b*-value used in the rate determinations; the error in return period for some fault segments may be a factor of about three (Molnar, 1979). Recurrence rates obtained from trenching studies, considering only reasonable uncertainty in paleoearthquake size, may range over a factor of two (e.g., Thenhaus and others, 1980). Campbell (1983) reports a coefficient of variation (standard deviation divided by mean) of 2.77 for slip-based recurrence estimates for faults in southern California. When used as Bayesian priors, to be updated by historic occurrence rates, geological slip-rate recurrences with coefficients of variation larger than 1.0 are easily dominated by the historic rates in California (Campbell, 1983).

Recurrence estimates for characteristic earthquakes are often determined by trenching studies in which the organic materials entrained in the rupture or having fallen into the fault are dated. In these cases, the recurrence rates have considerably less variability than slip-determined rates, and may reasonably be preferred over rates determined by extrapolating historical seismicity in the Gutenberg-Richter relationship. In the following discussion on the variability of rate in hazard estimates, we will consider historical rates because historical earthquakes are generally used as the basis for estimating seismicity parameters in most of the U.S.

Estimating Seismicity Parameters and Their Uncertainties

If a complete record of earthquake magnitudes and locations during a time period of length t were available for an area, and we made the usual assumption that earthquakes have an exponential interoccurrence time distribution (Poisson process), our maximum likelihood estimate of the number of earthquakes expected in the area during time intervals of length t, would be N the number observed; and our best estimate of the standard deviation in the number expected during various intervals of length t would be $\sigma_N = \sqrt{N}$. (For sample sizes often found in hazard analyses this represents a rate uncertainty ranging from 10 to 30 per cent.) The standard deviation of the estimated b-value resulting from sample-to-sample variability would be approximately $\sigma_b = b/\sqrt{N}$. (In typical applications, these uncertainties might range from 10 to 30 per cent of the estimated b-value.) However, in practice, the actual uncertainties in rates and b-values are higher than stated above, because of the problems noted earlier, i.e., data is missing, earthquakes are mislocated and magnitudes are inexact. Estimating uncertainties from these factors requires making assumptions regarding the size and distribution these errors.

Various assumptions regarding the data and the use of different fitting techniques (e.g., maximum likelihood and least squares procedures) may yield considerably different estimates of rates and b-values. Weichert (1980) uses a reduced data set to estimate a rate and b-value. Earthquakes are grouped by magnitude into a number of intervals, ($m_i \leq m \leq m_{i+1}$; $1 \leq i \leq n-1$; $m_n = m_{max}$), and the time periods for which magnitudes in each interval have been completely recorded are estimated. The analysis then considers only earthquakes that occurred during time periods for which the data is regarded as complete. EPRI/SOG (1987) discusses a procedure for jointly estimating rates, b-values and the probability of having detected a random earthquake as a function of time, magnitude and location. The joint estimates of these parameters show a high covariance, e.g., the b-value estimate is highly correlated with the estimate of the probability of detection as a function of magnitude. The authors note that the estimates may have a large statistical uncertainty, and suggest fitting the model with fewer parameters or constraining the values of some of the parameters.

We conclude error bars on rates and b-values will be considerably wider than predicted by the statistical variability in unbiased random samples, depending additionally on prior treatment of the data and choice of fitting technique.

We note that in maximum likelihood estimation (which we prefer to least squares, e.g., Bender, 1984), if the record is complete for T years, the estimate, $\hat{R}$, of the annual rate R is $\hat{R} = N/T$, where N=the number of earthquakes observed during T years. We note especially that $\hat{R}$ depends only on the number of earthquakes observed, and is independent of the magnitudes of these earthquakes. If the observed earthquakes are grouped by magnitude into a number of intervals in the range $m_{min} \leq m \leq m_{max}$, the maximum likelihood estimate $\hat{b}$ is the most likely value of the Gutenberg Richter b-value, given the relative frequency of earthquakes in the various magnitude intervals. For all practical purposes, we can state that the estimate $\hat{b}$ does not depend on the number of earthquakes in the sample, only on the fraction of earthquakes in each magnitude interval. (If earthquakes are grouped by magnitude into k intervals, only a finite number of combinations of n_1

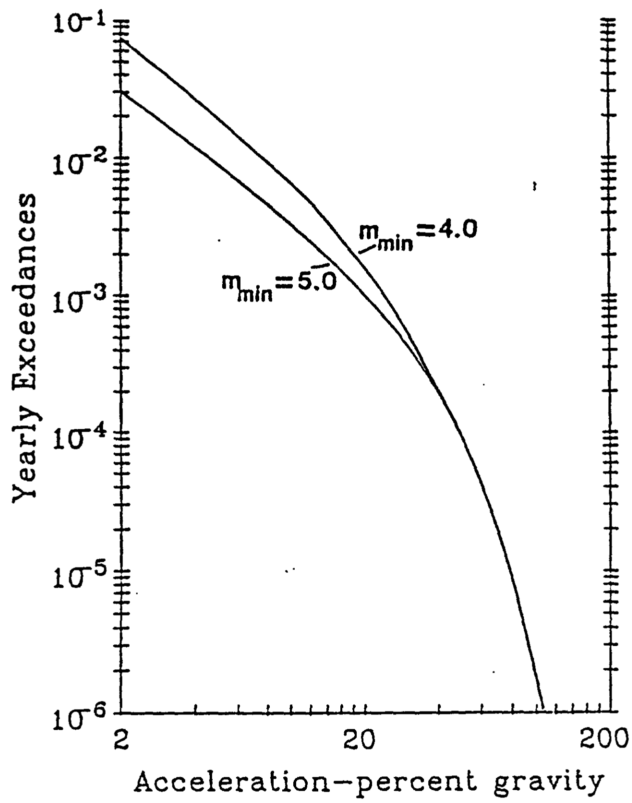

Figure 1. Annual exceedance rates of various levels of peak horizontal acceleration at a site at the center of a square source 220 km by 220 km calculated for $m_{min} = 4.0$ and $m_{min} = 5.0$ using the attenuation relationship of Campbell (1987):

$$\ln(A) = -3.303 + 0.85M - 1.25\ln[R + .0872\exp(.678M)] - .0059R$$

where $R = \sqrt{r^2 + d^2}$, r=surface distance to closest point of the surface projection of seismogenic rupture; d = 2=depth of seismogenic rupture. When $m_{min} = 4.0$ was assumed, a rate of one earthquake in the range $4.0 \leq m \leq 7.0$ was used; when $m_{min} = 5.0$ was assumed, expected earthquakes in the range $4.0 \leq m < 5.0$ were ignored; for both calculations a b-value of $b = 0.85$ and $\sigma = 0.3$ in ln-accleration were assumed. Median rupture-lengths in the magnitude-rupture length relationship of Slemmons (1982) were used, assuming an inferred field of faulting parallel to one edge of the source.

earthquakes in the first interval, n_2 in the second, etc., ($N = n_1 + n_2 + ...n_k$) are possible. For each combination, a different $\hat{b}$ is estimated. A set of N earthquakes, and a set of $N + 1$ earthquakes, for example, cannot have exactly the same number of earthquakes in each magnitude interval, and different estimates of b will result for sets of N and $N + 1$ earthquakes. More generally, different numbers of earthquakes can yield different possible values of $\hat{b}$. However, unless N is small, we can ignore these differences.) We conclude that, in effect, the rate estimate is *decoupled* from the estimate of the b-value. This means we can make no inference about the rate of earthquakes based on the magnitude distribution of the observed earthquakes, and conversely, we can make no inference about the b-value based on the number of earthquakes observed. Hence, in our analysis, we treat $\hat{R}$ and $\hat{b}$ as independent.

The maximum possible magnitude, m_{max}, of earthquakes in a region cannot be reliably estimated statistically from observed earthquake magnitudes, even if these magnitudes are recorded without error, unless the observed maximum magnitude is lower and the data set is larger than is usually available in practice. For that special case the uncertainty in estimated maximum magnitude, $\hat{m}_{max}$, may be as little as 0.25 magnitude units, but generally the uncertainty can be shown to be one or two magnitude units or more (Bender, submitted). Considerations of geological analogy may serve to constrain the estimated maximum magnitude more than statistical considerations in some cases, but in areas of low seismicity and sparse geological data on recent faulting, the uncertainty in maximum magnitude remains high.

A single value of minimum magnitude, m_{min}, is typically used in seismic hazard calculations. M_{min} is usually selected to represent a probable lower bound for damaging earthquakes, and different authors choose different values of m_{min} because of uncertanty as to the significance of large-amplitude, high-frequency ground motions originating from small-magnitude earthquakes. Bender and Campbell (1989) suggest that a tapered minimum magnitude be used if one believes that some (but not all) of the higher ground motions from smaller earthquakes may be damaging. The minimum magnitude used in recent calculations by different authors ranges from $m_{min} = 3.6$ to $m_{min} = 5.0$. Figure 1 illustrates yearly exceedance rates of various levels of peak horizontal acceleration calculated at a site at the center of an areal source zone when the calculations were done assuming $m_{min} = 4.0$ and when they were done for $m_{min} = 5.0$, using the same attenuation function and setting $m_{max} = 7.0$ in both cases. In this example, the ground-motion level calculated to have an annual exceedance rate of 0.002 was 0.18 g when $m_{min} = 4.0$ was assumed and 0.13 g. when $m_{min} = 5.0$ was used. The differences in calculated ground-motion levels are most significant at the lower ground motion levels corresponding to higher exceedance rates.

A Single Best Hazard Estimate from Uncertain Seismicity Parameters

If we assume a discrete distribution of rates R_i, $i = 1, ..I$, of b-values, b_j, $j = 1, ..., J$, and of maximum magnitudes $m_{max(k)}$, $k = 1, ..., K$, we can calculate a histogram of expected ground motions for each combination of R_i, b_j, and $m_{max(k)}$. We can then weight the ground motions calculated for each combination, R_i, b_j, $m_{max(k)}$, for each entry in the histogram by the probability assigned to this combination of input values, and then finally obtain a weighted average of the calculated ground-motion rates. Given these rates, we can calculate the probability that a ground-motion level will be exceeded during one year, and the probability that it will be exceeded during t years. Note that this approach requires calculating ground motions for $I \cdot J \cdot K$ input combinations.

Calculations for each set of input values are done numerically by first dividing the magnitude range into a number of intervals, determining the expected number of earthquakes in each interval (based on the overall rate, b-value and maximum magnitude), and assuming the earthquakes in each magnitude interval occur at the center of the interval. We can eliminate most of the ground-motion computations and more easily obtain the same average histogram of ground-motion rates if we first integrate the number of earthquakes in each magnitude interval over the assumed distributions of R, b and m_{max}, and then

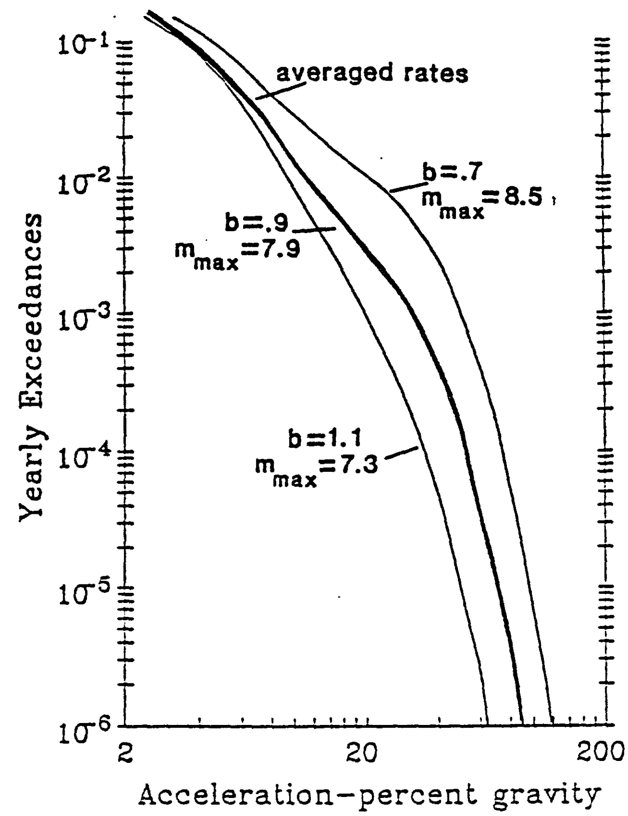

Figure 2. Annual ground-motion exceedances calculated at a site 10 km from the center of a 280 km long fault, assuming $m_{min} = 4.0$ and $R = 1$ earthquake in the given magnitude range when (a) earthquakes in each magnitude interval are averaged, b has a triangular distribution in the interval $0.7 \leq b \leq 1.1$, and m_{max} has a uniform distribution in the range $7.3 \leq m_{max} \leq 8.5$; (b) the central values of $b = 0.9$ and $m_{max} = 7.9$ are used; (c) the extreme values ($b = 0.7, m_{max} = 8.5$) and (d) the extreme values ($b = 1.1, m_{max} = 7.3$) are used. The attenuation function of Campbell (1987) (with $\sigma = 0.3$) and median lengths in the magnitude-rupture length relationship of Slemmons (1982) were used.

calculate ground motions using these rates. In this case, the "best estimate" of the ground motion having probability p of not being exceeded during t years is calculated using the integrated (averaged) earthquake rates.

We note the rather obvious fact that if R varies independently of b and m_{max}, and if R is symmetrically distributed about a central value $\bar{R}$, the average number of earthquakes in a magnitude interval obtained for a fixed value of b and m_{max} by integrating over R is exactly equal to the value given by $\bar{R}$. However, using a central value of maximum magnitude $\bar{m}_{max}$ cannot give exactly the same number of earthquakes in each magnitude interval as obtained by integrating over values of m_{max}. (Using the average value $\bar{m}_{max}$ implies no earthquakes with magnitudes $m > \bar{m}_{max}$ occur, whereas integrating over possible values of m_{max} means earthquakes with magnitudes $m > \bar{m}_{max}$ appear in the calculations.) Similarly, the rates in each magnitude interval obtained by integrating over b are not identical to the rates given by the central value of b. However, so long as the assumed distributions of b and m_{max} are symmetric about the their mean values, $\bar{b}$ and $\bar{m}_{max}$, exceedance rates calculated using $\bar{b}$ and $\bar{m}_{max}$ are generally similar to those obtained by integrating the earthquake rates in each magnitude interval over b and m_{max}. The differences may become significant at the higher ground motions, particularly if no variability in the attenuation (see below) is assumed, but for most hazard map purposes, the differences can be ignored.

Figure 2 illustrates annual ground-motion exceedances calculated at a site 10 km from the center of a 280 km long fault, when (a) earthquakes in each magnitude interval are averaged, assuming $R = 1$ earthquake in the given magnitude range for each scenario, b has a triangular distribution in the interval $0.7 \leq b \leq 1.1$, and m_{max} has a uniform distribution in the range $7.3 \leq m_{max} \leq 8.5$; (b) the central values of $b = 0.9$ and $m_{max} = 7.9$ are used; (c) the extreme values ($b = 0.7, m_{max} = 8.5$) and (d) the extreme values ($b = 1.1, m_{max} = 7.3$) are used.

We conclude that to obtain an approximate mean estimate of ground-motion exceedance rates, it is not necessary to integrate over uncertainty in earthquake rates, b-values and maximum magnitudes in seismic hazard calculations, if these parameters are assumed to be symmetrically distributed about their central (mean) estimates ($\bar{b}$, $\bar{R}$ and $\bar{m}_{max}$). Using the central values is adequate in this case. (We note that averaging earthquake rates in each magnitude interval over the range of b and m_{max} and then doing a single calculation to determine the ground motion with a given probability of exceedance is not equivalent to calculating the ground motion with that exceedance probability for each combination of b-value and maximum magnitude and then averaging the calculated ground motions.)

Point- versus Rupture-Sources

Typically earthquakes in areal sources have been modeled as points, although earthquakes occurring along faults have been modeled as finite-length, linear ruptures. However, most current attenuation functions evaluate ground motions for the closest site-to-rupture distance or closest distance to the surface projection of the rupture (e.g., for a summary listing of these functions, see Joyner and Boore, 1988, or Campbell, 1985).

Figure 3 illustrates the differences in ground motions calculated at a site in an areal source zone using the attenuation of Campbell (1987), when earthquakes are treated as points, and when finite-length ruptures are assumed. (The ruptures are in an inferred field of faults in which the direction of the faulting is parallel to one edge of source.) The rupture lengths represent median lengths in the relationship of Slemmons (1982) and median lengths in the relationship of Bonilla and others (1984).

We conclude that we are probably routinely underestimating the hazard from earthquakes in areal sources, when we model these earthquakes as points, but use an attenuation function that assumes finite length ruptures. We believe earthquakes should be modeled as ruptures in the hazard calculations, using some reasonable rupture-length magnitude relationship, when such an attenuation function is used. However, we further believe that the rupture-length magnitude relationship selected is generally not one of the larger sources of uncertainty in hazard mapping and it is, therefore, reasonable to to use a single relationship, or to average exceedance rates obtained using several rupture-length magnitude relationships. For simplicity, we prefer using a single relationship for the calculations for the hazard map, but also doing the calculations for at least one alternative rupture-length magnitude relationship at a number of sites representing different geometries and seismicity rates. The latter approach enables us to identify the conditions under which the

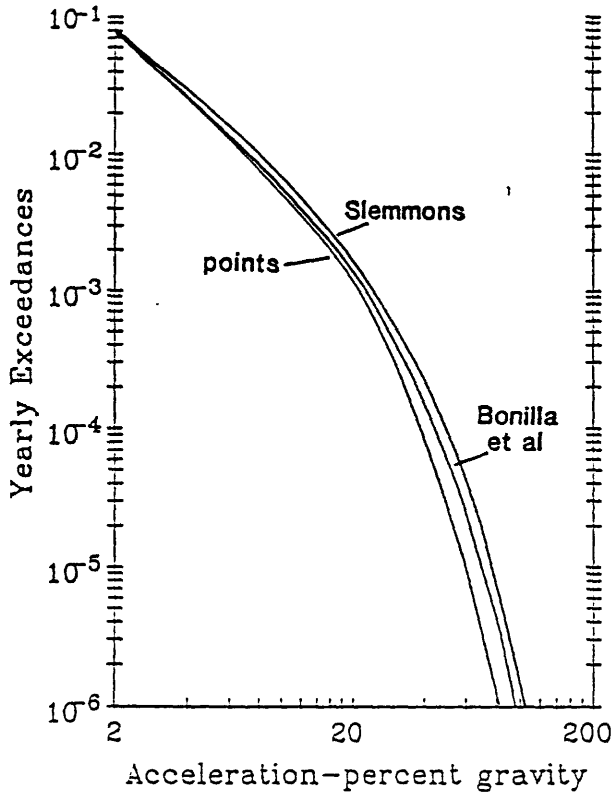

Figure 3. Annual ground-motion exceedances calculated at the same site using the same values of the seismicity parameters as in Figure 1 (with $m_{min} = 4.0$), when point source earthquakes are assumed, and when finite length ruptures are assumed. Median rupture lengths in the magnitude-rupture length relationship of Slemmons (1982), and median lengths in the relationship of Bonilla and others (1984) were used. The attenuation function is that of Campbell (1987) (with $\sigma = 0.3$).

rupture length magnitude relationship is a more important source of uncertainty.

Variability in Rupture Length vs Magnitude Relationship

The variability in rupture lengths for each magnitude is usually assumed to be lognormally distributed. Integrating over this distribution of lengths can, under some conditions, significantly increase the calculated exceedances of a ground-motion level above those calculated using only median rupture lengths (the values generally fit by a regression of log rupture length on magnitude) (Bender, 1984a). The ground-motion exceedances calculated using a mean (rather than median) rupture length tend to be more nearly equal to those calculated by integrating over a lognormal distribution of lengths.

Uncertainty in Ground-Motion Attenuation

We consider here two kinds of variability that affect calculated ground motions: the variability in ground motions resulting from different earthquakes, which we term *ground-motion variability*, and the variability that results from *uncertainty in the choice of the attenuation function.*

Ground-Motion Variability

Attenuations functions typically give a median ground motion for earthquakes of each

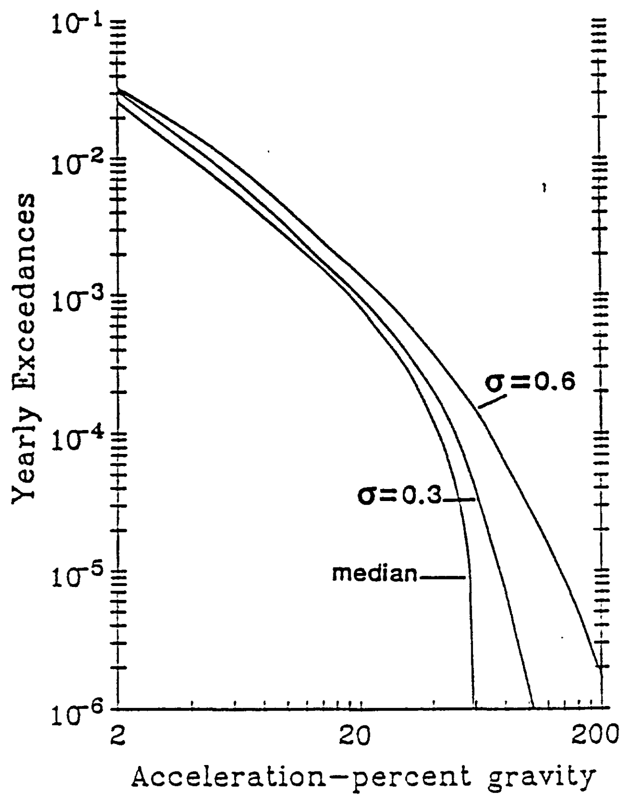

Figure 4. Annual ground-motion exceedances calculated for the same site and using same seismicity parameters as in Figure 1, assuming $m_{min} = 5.0$. The calculations were done using median values ($\sigma = 0$) and assuming $\sigma = 0.3$ and $\sigma = 0.6$ in the attenuation relationship of Campbell (1987).

magnitude and distance. Most authors assume that ground motions resulting at a site from random earthquakes of a given magnitude and distance are *lognormally* distributed about the median value, and provide a value of σ, the standard deviation of log ground motion, where σ is independent of magnitude and distance (However, a few authors, e.g., Idriss, 1987; Sadigh and others, 1986, as referenced in Joyner and Boore, 1988, propose attenuation relationships in which σ is magnitude dependent.) Including ground-motion variability may significantly increase the ground motion levels calculated to have a fixed probability of exceedance above those calculated when only median ground motions are assumed for earthquakes of each magnitude and distance (e.g., Bender, 1984b). The value of σ that is used in the calculations becomes important. Figure 4 shows annual expected exceedances of various ground-motion levels when the calculations are done for a site at the center of a square source 220 km by 220 km using median values ($\sigma = 0$) in the attenuation relationship of Campbell (1988, equation 5), and when they are done assuming $\sigma = 0.3$ and $\sigma = 0.6$ (in natural logarithm of ground motion). (In Figure 4 and in other figures in this paper, σ is independent of magnitude and distance.) We observe that if median ground-motion values are used in the calculations, no ground motion higher than the median motion produced by the largest magnitude earthquake at the closest distance to the site can be predicted, and hence mapped ground motions will have an upper bound. However, if ground-motion variability is taken into account, very high ground motions will be predicted for some earthquakes, and the mapped ground-motion levels can become very high, particularly for long return periods and large values of σ.

Using *mean* ground motions predicted by the attenuation function results in somewhat larger probabilistic ground-motion levels than are obtained if *median* ground motions are used in the calculations. At lower probabilistic ground-motion levels, using mean ground-motion values for earthquakes of each magnitude and distance may give a fairly good approximation to the results obtained by integrating over ground motions; however there will continue to be an upper bound to calculated ground-motion levels, and fewer exceedances of the higher ground-motion levels at a site will be calculated than when ground-motion variability is taken into account.

The value $\sigma = 0.6$ (in natural logarithm of the ground motion) is typically used in seismic hazard calculations. A considerably lower value, $\sigma = 0.3$ was reported by Campbell, 1987, who developed an attenuation relationship based on strong-motion recordings of worldwide earthquakes with magnitudes in the range $5.0 \leq m_s \leq 7.0$. Unlike most other authors, Campbell includes terms in his equations for fault type, source directivity, shallow soil, building size and embedment. By including these additional terms, Campbell was able to reduce the variability about the fitted values below that determined by authors who do not adjust for site and source conditions.

Calculating the hazard with ground-motion variability of $\sigma = 0.6$, instead of using median ground-motion values, may increase the probabilistic ground-motion level for a given time period by 10 to 40 per cent at sites in the eastern U.S. At sites in California near active faults, ground-motion levels may increase by a factor of 2.0 or more at long return periods. Including ground-motion variability in the calculations (as compared with using median values only) increases the calculated ground-motion levels by greater amounts at longer return periods. When attenuation variability is included in the calculations, the fractional increase in the calculated ground motion levels may be quite different at different sites, and may be difficult to predict by "rule of thumb" techniques when various source geometries and earthquake rates are considered.

We suggest that because assumptions regarding attenuation variability can significantly affect the calculated probabilistic ground-motion levels, the attenuation function should be designed for particular site conditions whenever possible (reducing the value of σ below that obtained when data for different site conditions are combined), and the value selected for σ should be realistic rather than overly conservative.

Uncertainty in Choice of Attenuation Function

The second source of uncertainty lies in the median ground-motion values predicted by the attenuation function. Attenuation functions are usually derived by fitting equations to strong-motion data. Many of the attenuation functions that have been proposed use subsets of the same data and show reasonable similarity in predicting ground motions within the limits of that data. However, the data are generally restricted to a relatively narrow range of magnitudes and distances. For very short distances, for long distances, and for high-magnitude earthquakes, different attenuation functions tend to predict different ground motions. As with the effect of σ on the calculations, there is no easy "rule of

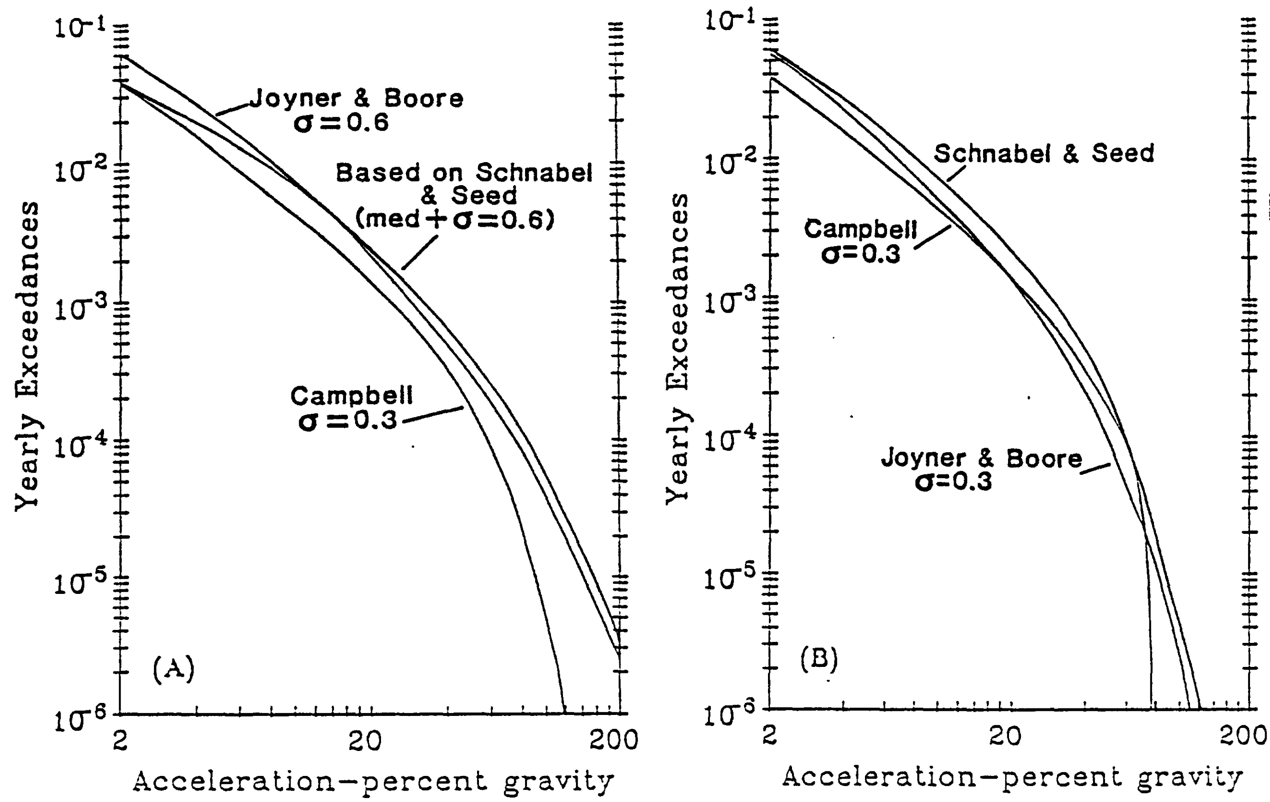

Figure 5. (A) Annual ground-motion exceedance rates calculated at the same site and using the same seismicity parameters as in Figure 3, using the attenuation relationship of Joyner and Boore (1981) with $\sigma = 0.6$; using the equation of Campbell (1987) with $\sigma = 0.3$; using the Schnabel and Seed (1973) curves; and using curves derived from the Schnabel and Seed (1973) curves by assuming the latter curves represented mean ground motions, reducing the ground motions to median values and doing the calculations with $\sigma = 0.6$. (B) Ground-motion exceedance rates calculated using the Joyner and Boore (1981) and Campbell (1987) equations setting $\sigma = 0.3$ in both cases.

thumb" that can be applied to predict how using various attenuation functions will alter the calculated probabilistic ground motions, these motions depending on the distance from the site to the dominating source, the return period chosen, the geometric configuration of the sources, the number and distance of the large magnitude earthquakes, etc.

If we compare results using different attenuation functions, we must be certain that the functions are being used consistently. For example, Campbell (1987) separates strike-slip from reverse thrust earthquakes, whereas, Joyner and Boore (1981) group together both types of faulting in their model. Campbell suggests using an average for the two types of faulting in his equations if one wishes to compare his equations with those of Joyner and Boore (Campbell, personal communication, 1989). Campbell requires specifying the distance to seismogenic rupture; Joyner and Boore use the closest distance to the surface projection of the rupture. Grouping together data representing various source and site conditions, Joyner and Boore estimate $\sigma \approx 0.6$ in the natural logarithm of ground motion, whereas Campbell, who includes parameters for fault type, site conditions, etc., estimates $\sigma = 0.3$.

Figure 5A shows ground-motion exceedances calculated at the same site as in Figure 4 using the equation of Joyner and Boore (1981) with $\sigma = 0.6$; using the equation of Campbell (1987) with $\sigma = 0.3$; and using an attenuation relationship based on the modified Schnabel and Seed (1973) curves with $\sigma = 0.6$, that was used in a recent map by Algermissen and others, (to be published as a U.S. Geological Survey MF Series publication). (Assuming the Schnabel and Seed curves represent mean ground motions, Algermissen *et al.* modified the curves by reducing the mean ground motions to median ground motions for $\sigma = 0.6$.) Figure 5B shows results calculated using the Campbell and the Joyner and Boore attenuation functions, when $\sigma = 0.3$ is assumed in both cases, and also using the (original) Schnabel and Seed (1973) curves with no ground-motion variability. (Schnabel and Seed curves were used without variability in producing national seismic hazard maps (Algermissen and Perkins, 1976, Algermissen and others, 1982).) We note that the results obtained using the Schnabel and Seed mean curves are generally quite close to results obtained using the Joyner and Boore curves with $\sigma = 0.3$ (Figure 5B) and the curves based on median Schnabel and Seed curves $\sigma = 0.6$ are quite similar to those obtained using the Joyner and Boore curves with $\sigma = 0.6$ (Figure 5A). The differences in this example are greater when a single attenuation function is used and σ is changed from $\sigma = 0.3$ to $\sigma = 0.6$ than when different attuenuation functions with the same σ are used. (Compare Figures 4, 5A and 5B for the Campbell and the Joyner and Boore attenuation functions).

There is currently no general agreement on which of the recent attenuation relationships to use in hazard calculations. Common practice has been to select and use one attenuation function, the properties of which are well known, or to average the results of analyses undertaken with several different attenuation functions. Although it seems reasonble to average results or to use an "average" attenuation function, the question of how to construct an average attenuation function (and the value of σ to use) is controversial, as is the question of how to determine the criteria to use in selecting alternative attenuation functions and the weights to apply to results obtained using each of these functions. One might reasonably argue that several attenuation functions with different properties should be selected and given equal weights; we believe the question of how to determine the attenuation functions to use in producing a seismic hazard map requires additional investigation before decisions are made.

Locational Uncertainty of Source Boundaries

In most hazard analysis computer programs, areal sources are required to have well-defined boundaries, and modeled earthquake rates, b-values and maximum magnitudes often change abruptly at these boundaries. This can have the effect that the calculated probabilistic ground-motion levels will change significantly at sites a short distance apart near the boundary of a source. A considerably lower probabilistic ground-motion level may be calculated for a given time period for a site 5 kilometers outside a source zone, for example, than for a site on the source boundary; the fractional difference in the calculated ground motion levels at the two sites increases as the time period increases. However, in fact, seismically homogeneous areas seldom have clearly defined boundaries, seismicity does not change abruptly, at hypothetical boundaries, and large changes in probabilistic ground motions at nearby sites are not desirable. Therefore, seismicity should be modeled as changing gradually rather than abruptly at source boundaries, or equivalently, the locations of these boundaries should be regarded as uncertain. Boundary location uncertainty has been discussed by Bender (1986), and the ability to treat source boundary locations as uncertain has been implemented in the USGS computer program SEISRISK III (Bender and Perkins, 1987).

Alternative Source Zones

Alternative source zone scenarios may be used to represent uncertainty in source zone boundaries, and to represent uncertainty in the tectonic principles used to define source zones. A significant number of authors now consider a number of distinct alternative source zone scenarios, including a set of earthquakes rates, *b*-values and maximum magnitudes for each scenario; they may also include several attenuation functions in their analysis. These authors assign weights to each combination of values of the input parameters, and evaluate hazard at each site for all possible combinations of values (the logic-tree approach). Other authors assume a set of altnerative source zone scenarios, and a distribution of rates, *b*-values, etc. These authors evaluate ground motions for a large number of values of the input parameters, where each value is randomly selected in accordance with the assumed distributions (Monte-Carlo approach). Both the authors who use a logic-tree approach and those who use a Monte-Carlo approach can determine a distribution curve for the calculated probability of exceeding various ground-motion levels at a site under the various assumptions.

Although a cumulative probability curve can be presented to represent hazard a specific site, by contrast, a seismic hazard map shows only a single estimate of ground motion for each site, and the question arises how to select that single estimate. It might seem logical to calculate the mean or select the median value from the cumulative probability curve, but we believe either of these alternatives could give a false impression of hazard at the site, particularly when alternative source zone scenarios representing different tectonic principles are modeled. As a simple example, let us assume that, in one scenario, an active fault is near a site, and the hazard is "high"; in the alternative scenario, the fault is not active, earthquakes are distributed in the background, and the hazard at the site is "low." The average hazard is "moderate," but this average does not represent hazard for any real scenario, and designing for "moderate" hazard will be an overdesign if the true hazard is "low" and an underdesign if the true hazard is "high." As a second example, let us imagine three scenarios, with weights 0.4, 0.11, and 0.49 respectively, such that the hazard estimates at a site for the first scenario are lower than the hazard estimates for the second scenario, and those for the second scenario are lower than those for the third scenario. The median hazard (and possibly the average hazard) will be associated with the second scenario, which is the least likely of the three scenarios.

A further problem with averaging over alternative zonations in hazard mapping is that generally unduly low ground-motion levels are predicted in the vicinity of concentrations of historical seismicity, because of the "diluting" effect on the seismicity of alternative zonations. This same dilution of seismicity tends to increase predicted ground-motion levels at sites of low historic seismicity, which may possibly be a desirable or conservative effect, but which has the consequence that the map generally shows a lower range of ground motion values than it would for any single scenario (Thenhaus and others, 1987), and does not permit a clear understanding of the sources of variability.

We believe that the ground-motion levels in a seismic hazard map should represent a specific source-zone scenario, rather than show a mean or median value of a range of scenarios, and that if alternative source-zone scenarios are considered, the results should be shown on separate maps (e.g., Thenhaus and others, 1987). We believe that, generally, a scenario that should be considered is one that consists primarily of source zones based on historic seismicity, in order that the ground motions on at least one map will show the consequences of assuming a continuation of the historic seismicity.

Should Hazard Maps Show Extreme Values?

We believe it is feasible to provide error bars or to contour separately ground motions corresponding to the estimated 15 per cent and 85 per cent cumulative probability levels in a seismic hazard map for a given source zone scenario, in order to represent the uncertainty resulting from uncertainties in the values of earthquake rates, *b*-values and maximum magnitudes for each zone. We could, in principle, also consider a set of attenuation functions, and show error bars for the results obtained using these functions, although, we are uncertain at this time, how to select and weight such functions. However, we have concerns regarding the advisability of presenting uncertainty estimates in a seismic hazard map (as contrasted with site specific studies) when different source-zone scenarios are considered.

An empirical probability distribution and confidence limits for the ground-motion levels, constructed using either logic-tree or Monte Carlo techniques, obviously depend on the alternatives that are included, and on the weights or probabilities that are assigned to each alternative. In the case of site specific ground-motion studies, it may be practical to make a comprehensive, detailed investigation of the possible sources of hazard and to carefully evaluate all the theories that have been proposed; in the case of producing a national hazard map, we probably do not have the manpower to evaluate a very large set of alternatives, incorporate these into the computer porgram and do the calculations at each site.

Recognizing that a considerable amount of labor and judgment is required to set up the inputs for a Monte-Carlo simulation or to exhaustively evaluate alternatives using a logic-tree approach, in answering the question "Is it desirable to provide contours of ground-motion levels that will be exceeded in 15 per cent and 85 per cent (or some other fraction) of the calculations for the assumed distributions of the input parameters?" we should perhaps consider:

1) Is an 85 per cent contour level useful in any practical sense? If an engineer incorporates additional safety factors when making use of the estimated values contoured on seismic hazard maps, what is the practical value of having contours of the 85 per cent level? Would sufficient conservatism be available if maps for longer time periods were provided?

2) The fractional increase in ground motion levels between the ground motion

corresponding to the 50 percent probability value and the ground motion level corresponding to the 85 percent probability value will be different at different sites. If one wishes to compare relative ground-motion levels at two sites, how does one interpret different ground-motion ratios at the two sites for the between the mapped value and the 85 per cent level?

3) The calculated 85 per cent probability curves will be highly sensitive to assumptions regarding the distributions of the various input parameters. Do we want to base decisions on our best estimates of the basic parameters or on our estimates of distributions of those parameters?

Conclusions

A seismic hazard map should present probabilistic ground motions that were calculated by taking into account, as well as possible, uncertainties in the values of the various input parameters.

In the case of the seismicity parameters, one could properly take uncertainty into account by weighting and averaging the ground-motion exceedance rates obtained by doing the calculations for various combinations of earthquake rates, *b*-values and maximum magnitudes for each source. However, the same averaged result can be obtained more simply by doing a single calculation using earthquake rates that have been integrated over the range of the parameters. Moreover, if the uncertainty in the estimated earthquake rate, *b*-value and maximum magnitude for each source is assumed to be symmetrically distributed about the central value of each parameter, using the central value of each parameter should give a good approximation to the integrated result.

In the case of some other parameters, using a central value may not suffice. Thus, in using a single attenuation function, when we integrate over ground-motion variability we do not obtain the same results that we obtain when we use only a mean or median ground-motion value. (The differences in probabilistic ground motions become increasingly larger, especially at the higher ground motions, as σ, the assumed variability in log ground motion increases.) If we integrate over boundary location uncertainty when source-zone boundaries or source-fault locations are modeled with "fuzzy" boundaries to account for the uncertainty, we also may not obtain the same results as we obtain by using a single "hard" boundary at the center of the range of boundary locations. Thus, explicit integration is required in the case of these parameters.

In some other cases, using either a central parameter value or integrating over uncertainty may seem reasonable, but, in practice, either or both alternatives may be difficult to implement or may give results that are hard to interpret. For example, we may think it appropriate to use a central or average attenuation function, but not know how to construct such an "average" attenuation function, taking into account the different values of σ proposed by various authors, the different distance measures, etc. On the other hand, if we preferred to do the calculations using several of the recent attenuation functions and then average the results, the question of how to select these functions and the weights to apply to each could be controversial. We further note that the mapped ground motions may be biased, for example, if earthquakes in areal sources are modeled as points but attenuation relationships designed for rupturing sources are used.

In still other cases, one should probably not average or otherwise combine results to obtain a single estimate. In particular, we believe that if distinct alternative source zone scenarios are considered, the median result, or any averaging of the results, obtained using these different scenarios could give a misleading impression of hazard at a site. In addition to depending on the highly subjective weights applied to various source zone scenarios, an average hazard estimate may not represent hazard for any allowable scenario, and a median estimate may not represent hazard for one of the more likely scenarios. We believe the basis for considering different source zone scenarios should be clearly stated, and results obtained using these scenarios should be presented separately.

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POTENTIAL SOURCE EFFECTS ON PARAMETER VARIABILITY, ATTENUATION VARIABILITY AND GROUND MOTION MAPS

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INTRODUCTION

The U.S. Geological Survey(USGS) and the California Division of Mines and Geology(CDMG) are currently developing ground motion maps(GMM) or "contour maps." The CDMG has produced a draft deterministic acceleration ground motion map(AGMM) for the state of California. The USGS has started the development of a new generation of probabilistic ground motion maps(PGMM) for the United States. Individual maps will show isolines for a single ground motion parameter either independent of time(i.e. deterministic) or as a function of a particular level of risk or mean recurrance rate(i.e. probabilistic).

In simplest terms GMM's are constructed by:

1. locating and defining seismogenic sources or source regions;
2. estimating a time dependent or time independent magnitude relationship for each source or source region;
3. constructing a regional attenutation relationship;
4. estimating the amplitude of motion for a particular distance and level of risk; and
5. drawing the isolines.

The result is a "3-D" ground motion map (x,y,z format) that is clearly devoid of significant source, site and travel path factors. A primary reason for the "unnatural" look to these maps is the direct result of the nature of the "2-D" attentuation relationship and its use in estimating ground motion as a function of distance and magnitude. The attentuation relationship accounts for nearly all source, site and travel path affects in the model. However, attentuation relationships for the most part "filter" out these affects.

MODEL TEST

Inorder to better understand and evaluate the new generation of PGMM's a study was undertaken that would produce an AGMM independent of the general procedure to be used by the U. S. Geological Survey. The AGMM could then be compared to the PGMM and provide a means by which to check the results. Effects of the source on parameter/attenuation variability could also be reviewed.

The model used to construct the AGMM is relatively simple. It was assumed that acceleration data can be contoured or treated as x,y,z type information. An AGMM is therefore similar to a structural contour map in the method of construction. The control points used in construction of the AGMM are the location of the accelerograph stations(x,y) and peak accelerations(z) from the recorded accelerograms. The quality of the map is directly related to the density of the control points (Davis,1986).

Horizontal accelerograph ground-motion data recorded during the Imperial Valley, California, earthquake of October 15, 1979(IV79) was used in the construction of the AGMM's. IV79 was chosen because of its size(M_W=6.5) and because of the large number of accelerograms recorded within a relatively small region. Inorder to limit the size of the study region only stations where one or both of the recorded main-shock horizontal peak accelerations was equal to or greater than 0.05g.

To review possible source effects the peak horizontal acceleration data was divided into subgroups. Group one consisted of data recorded on accelerometers aligned approximately parallel to the strike of the Imperial fault(A0). The second group consisted of data recorded on accelerometers aligned approximately perpendicular to the strike of the Imperial fault(A90). Kanamori and Regan(1982) assumed a strike of N37W for the Imperial fault(they later computed a strike of N34W). Data used in this study is shown on Table I. The location of the accelerograph stations is shown on Figure 1.

AGMM's for A0 and A90 were computer generated. Isoacceleration lines were estimated by gridding combined with a distance weighted least squares interpolation. The resultant isoacceleration maps are shown on Figures 2 and 3.

DISCUSSION

Source

An important imput to the PGMM is a clear definition of the seismogenic source and/or source region. Important parameters include, among others, the size of the source(length or other physical dimension) and the size and frequency of expected earthquakes.

Shown on Figure 4 is a plot of isoacceleration lines for A0 and the trace of significant faults within the study area. The following should be noted:

1. Isoacceleration lines for the larger acceleration values correlate well with the observed surface rupture along the Imperial and Brawley faults;
2. Review of the shape of the isoacceleration lines relative to mapped faults suggests the possibility that faults other than the Imperial fault were also sources of recorded "main shock" ground motion;
3. Rupture noted along the San Andreas fault may have been aseismic; and
4. Recorded "main-shock" data may represent either several closely spaced events along the same fault(i.e. multiple event) or ground motion from an "extended" source that included variable energy release from several mechanically linked faults or fault segments.

The Cerro Prieto fault, the Imperial fault, the Superstition Hills fault, the Brawley fault and the Brawley seismic zone may represent the "extended" source or zone of energy release of IV79 "main shock" data. It is clear that the size of the events(if they can be considered as a series of individual earthquakes) on faults other than the Imperial were relatively small. However, the question remains is whether or not a "triggering mechanism" was involved in the development of what maybe a multiple event or is there a direct mechnical link(i.e. no fault-rupture barrier) to these faults and they represent a single fault segment.

Review of Figure 5 illustrates several other important aspects of the effects of the source on recorded "main-shock" ground motion. For example note the shift to the north of the A0-0.4g isoaccleration line as compared to the A90-0.4g isoacceleration line. The focusing of energy due to northward propagation of the rupture, reported by others, could explain the shift.

Another measure of the effect of the source on the AGMM is the total area confined by an individual isoacceleration line. Shown on Figure 6 is the ratio of the total area confined within an individual isoacceleration line for A0 and A90. It is clear that for larger accelerations or close to the fault the source has a significant effect on the shape, size and relative location of the isoacceleration lines.

<u>Attenuation</u>

Attenuation relationships are another important imput parameter in developing the PGMM. Attenuation relationships have been developed by a number of individuals since the 1971 San Fernando earthquake and before. The relationships were developed to illustrate how the amplitude of peak acceleration(or other ground motion parameter) decreases as a function of distance and magnitude. The result of these studies are curves that show the relationship between observed and predicted ground motion values.

Key elements of an attenuation study is how source/recording site distance is measured and how the "main-shock" data are partitioned.

Past studies for the most part have considered data recorded during a "main-shock" to be part of a homogenous data set relative to the source. Review of Figures 2,3 and 4 suggests the possibility that some of the "main-shock" data set was influenced by energy release along faults other than the Imperial or Brawley faults. For example if the peak accelerations recorded at sites near the Superstition Hills fault and the Brawley Seismic zone are the result of seismic slip along those structures should they be considered true "main-shock"(i.e. M_W 6.5) data for study of attenuation. Brune, and others(1982) noted a relatively large peak acceleration at Delta(Table 1, station no. 35), approximatley 33km from the Imperial fault. Delta however, is approximately 2+ km northeast of the Cerro Prieto Fault(Fig. 4).

If the Imperial and Brawley faults were the only significant source of recorded "main-shock" ground motion review of Figure 4 indicates that motion perpendicular to a fault(in this case a strike-slip fault) attenuates faster than motion radiated from the ends of a fault. The spacing or gradient of the isoacceleration lines is steeper perpendicular to the Imperial fault than off the ends of the fault.

Development of the PGMM with a single attenuation relationship could not account for observed directional source effects or variable attenuation rates.

Review of Figure 4 suggests that acceleration attenuation perpendicular to the Imperial fault is approximately symmetrical. Shown on Figure 7 is a comparison of attenuation A0 and A90 perpendicular to the Imperial fault break due south of the Brawley fault. Note that the largest isoacceleration value(i.e. 0.4g) attenuates relatively slow for A0 compared to A90 and that the reverse is true for the smaller acceleration values.

Shown on Figure 8 is a comparison of attenuation(less than or equal to 0.4g) northeast(NE) of the Imperial fault (Fig. 7) and attenuation relationships developed by Campbell(1981) and Joyner and Boore(1981). The Joyner and Boore(1981) curve(JB81) represents predicted 50 percentile values for a magnitude 6.5 event. The Campbell(1981) curve(KC81) is the predicted mean horizontal peak acceleration for the October 15, 1979 Imperial Valley earthquake. There appears to be a clear difference in the curves for distances less than and greater than 20+ km or approximately 0.15g. The reason(s) for the differences are not completely clear at this time. However, some of the differences are the result of how each of the above authors did or did not partition the "main-shock" data into subgroups. For example, as noted above, recorded peak acceleration at several of the stations near the Superstition Hills fault, Cerro Prieto fault and the Brawley seismic zone may have originated on other than the Imperial fault. If true, inclusion of these stations with the "main-shock" data set or measurement of distance from the Imperial fault would clearly skew the results of Campbell(1981) and Joyner and Boore(1981).

CONCLUSIONS

Results of the model test are clearly preliminary and significantly influenced by the number and location(i.e. density) of recording stations. The AGMM's (Fig. 2 and 3) show major trends in recorded peak acceleration data not local/large amplitude values like Bonds Corner. However, in developing the isoacceleration maps(AGMM) a number of interesting points came to light that are believed to be relevent to the development of the next generation of PGMM's.

1. Care is needed in the use of "main-shock" data in attenuation studies. Results of this study indicate that the 1979 Imperial

Valley Earthquake was a complex event that may have involved nonuniform(variable magnitude?) energy release along several faults and/or spreading centers. Hartzell and Heaton(1983) concluded that a relatively small event(M 5.0) occurred near the hypocenter south of the U.S. border and "grew into, or triggered a magnitude 6 earthquake north of the border." Source/recording site distance(and possibly magnitude) for distant stations(i.e. large distance from the surface trace of the main fault) maybe over estimated. It is not uncommon to assume that relatively large accelerations recorded at large distances are the result of unusual site or source conditions. In the case of Imperial Valley 1979 "large" distance peak accelerations can be explained inpart by release of seismic energy from faults other than the Imperial and Brawley.

2. Directional source effects are significant. It is clear that for larger peak acceleration values or close to the fault the source has a significant effect on the size, shape and relative location of the isoacceleration lines.

3. Results of this study suggests the possibility of a direct mechanical link or no fault-rupture barrier between the Imperial and Cerro Prieto transform faults and the Brawley and Cerro Prieto spreading centers along which strain is transmitted and seismic energy is released. The link which has been noted by others(Allen and others,1972 ; Thatcher 1979) also extends to the San Jacinto fault zone via the Superstition Hills fault. If there is a direct mechanical and seismogenic link from the Cerro Prieto fault on the south to the north end of the Superstition Hills fault and the southern terminus of the San Andreas: (1) what is the characteristic earthquake for this "extended" fault zone; and (2) can it be assumed for other fault zones that spreading centers and significant "gaps" between en echelon faults represent true fault-rupture barriers?

4. A similar study is being conducted using data from the 1971 San Fernando earthquake. Preliminary results support the findings of this study relative to the construction of PGMM's.

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TABLE 1
MAIN-SHOCK ACCELEROGRAPH GROUND MOTION DATA
IMPERIAL VALLEY,CALIFORNIA, EARTHQUAKE
OCTOBER 15, 1979

	Station Name	Cordinates Lat.	Long.	A0 (g)	A90 (g)
1	Brawley Air	32.988	115.509	0.22	0.17
2	Bonds Cor	32.693	115.338	0.66	0.81
3	Calexico F.S.	32.669	115.492	0.22	0.28
4	CalipatriaF.S.	33.13	115.52	0.09	0.13
5	Coachella 4	33.36	115.59	0.14	0.11
6	Co. Ser. Build	32.793	115.564	0.35	0.32
7	Imperial C.C.	32.79	115.56	0.24	0.24
8	El Centro 1	32.96	115.319	0.15	0.15
9	El Centro 2	32.916	115.366	0.33	0.43
10	El Centro 3	32.894	115.38	0.27	0.22
11	El Centro 4	32.864	115.432	0.61	0.38
12	El Centro 5	32.855	115.466	0.56	0.4
13	El Centro 6	32.839	115.487	0.72	0.45
14	El Centro 7	32.829	115.504	0.36	0.52
15	El Centro 8	32.811	115.532	0.64	0.5
16	El Centro 9	32.794	115.549	0.4	0.27
17	El Centro 10	32.78	115.567	0.23	0.2
18	El Centro 11	32.752	115.594	0.38	0.38
19	El Centro 12	32.718	115.637	0.15	0.11
20	El Centro 13	32.709	115.683	0.12	0.15
21	El C. Dogwood	32.796	115.535	0.51	0.37
22	Meloland Rd	32.773	115.448	0.32	0.3
23	Holtville P.O.	32.812	115.377	0.22	0.26
24	Niland F.S.	33.24	115.51	0.07	0.1
25	Parachute TS	32.93	115.7	0.2	0.11
26	Plaster City	32.79	115.86	0.07	0.05
27	Salton Sea WR	33.18	115.62	0.06	0.06
28	Super Mt. USN	32.955	115.823	0.21	0.12
29	Westmorland	33.04	115.62	0.11	0.08
30	Aeropuerto	32.651	115.332	0.24	0.316
31	Agrarias	32.621	115.301	0.28	0.227
32	Cerro Prieto	32.42	115.301	0.167	0.149
33	Chihuahua	32.484	115.24	0.263	0.267
34	Compuertas	32.572	115.083	0.149	0.188
35	Delta	32.356	115.195	0.349	0.235
36	Mexicali SAH.	32.618	115.428	0.311	0.459
37	Victoria	32.289	115.103	0.163	0.122

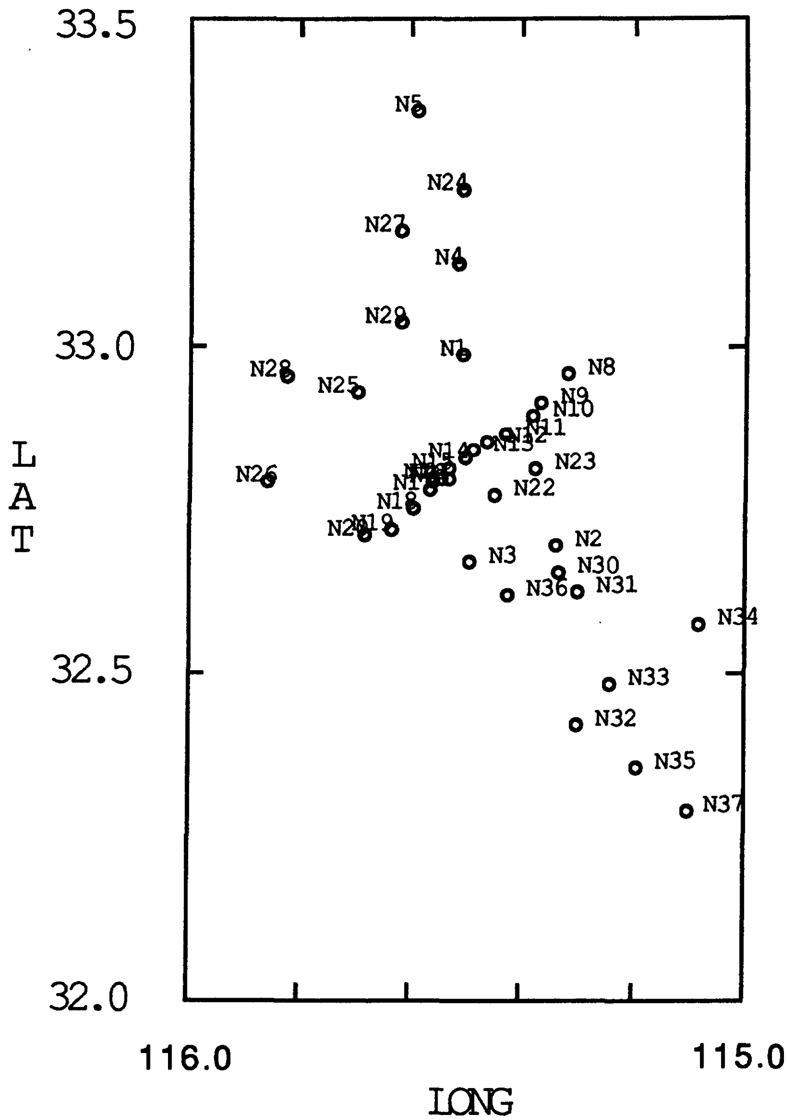

Fig. 1- Strong-motion stations in the Imperial Valley region that were operational during the October, 15, 1979 earthquake.

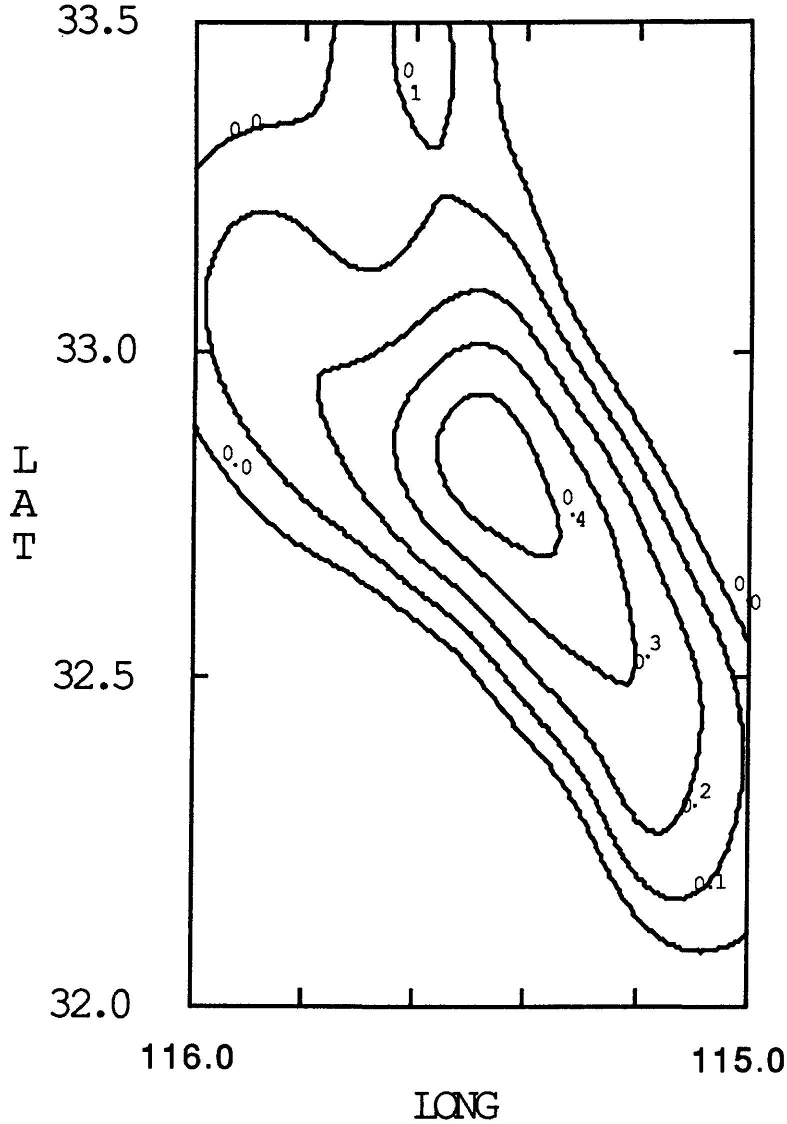

Fig. 2.-Isoacceleration map A0, Imperial Valley, California, earthquake of October 15, 1979.

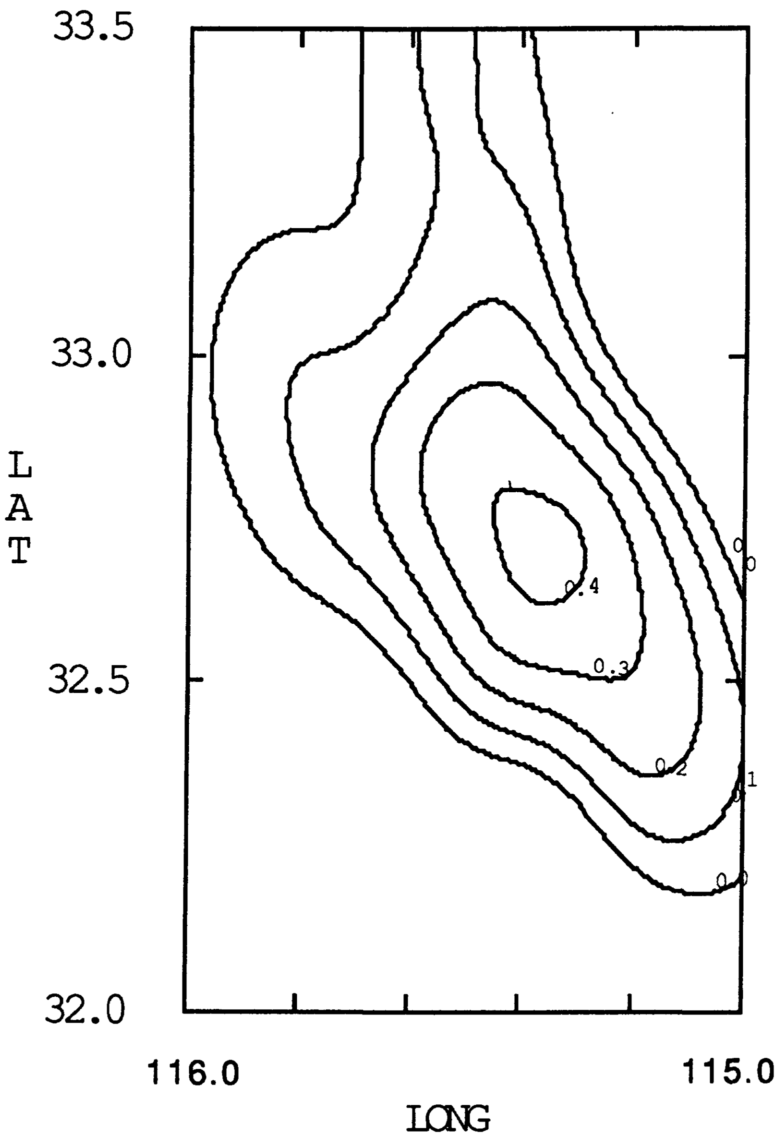

Fig. 3.- Isoacceleration map A90, Imperial Valley, California, earthquake of October 15, 1979.

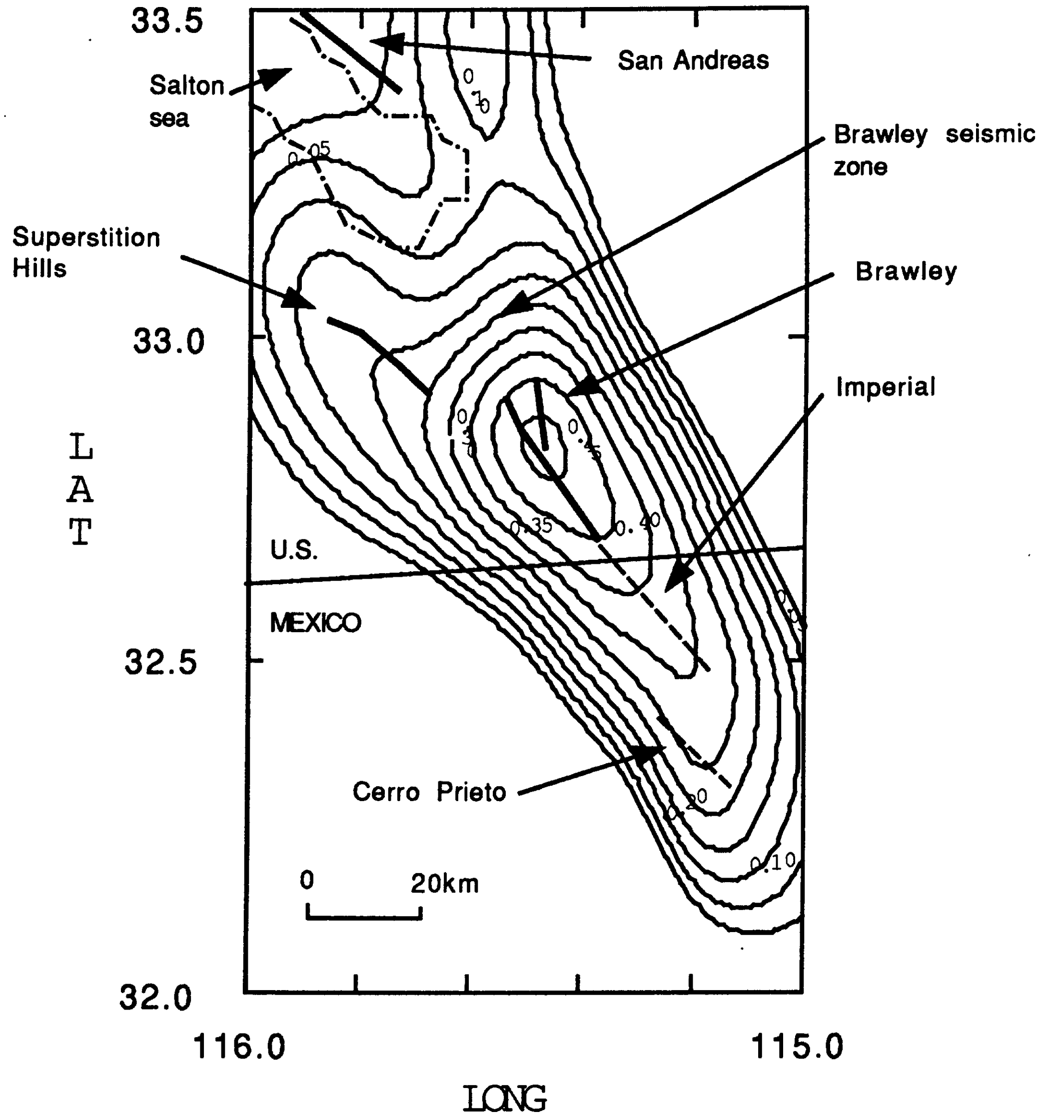

Fig. 4.-Isoacceleration map(A0), Imperial Valley, California, earthquake of October 15, 1979 and approximate location of significant faults within the study region(solid line approximate location of mapped surface breaks).

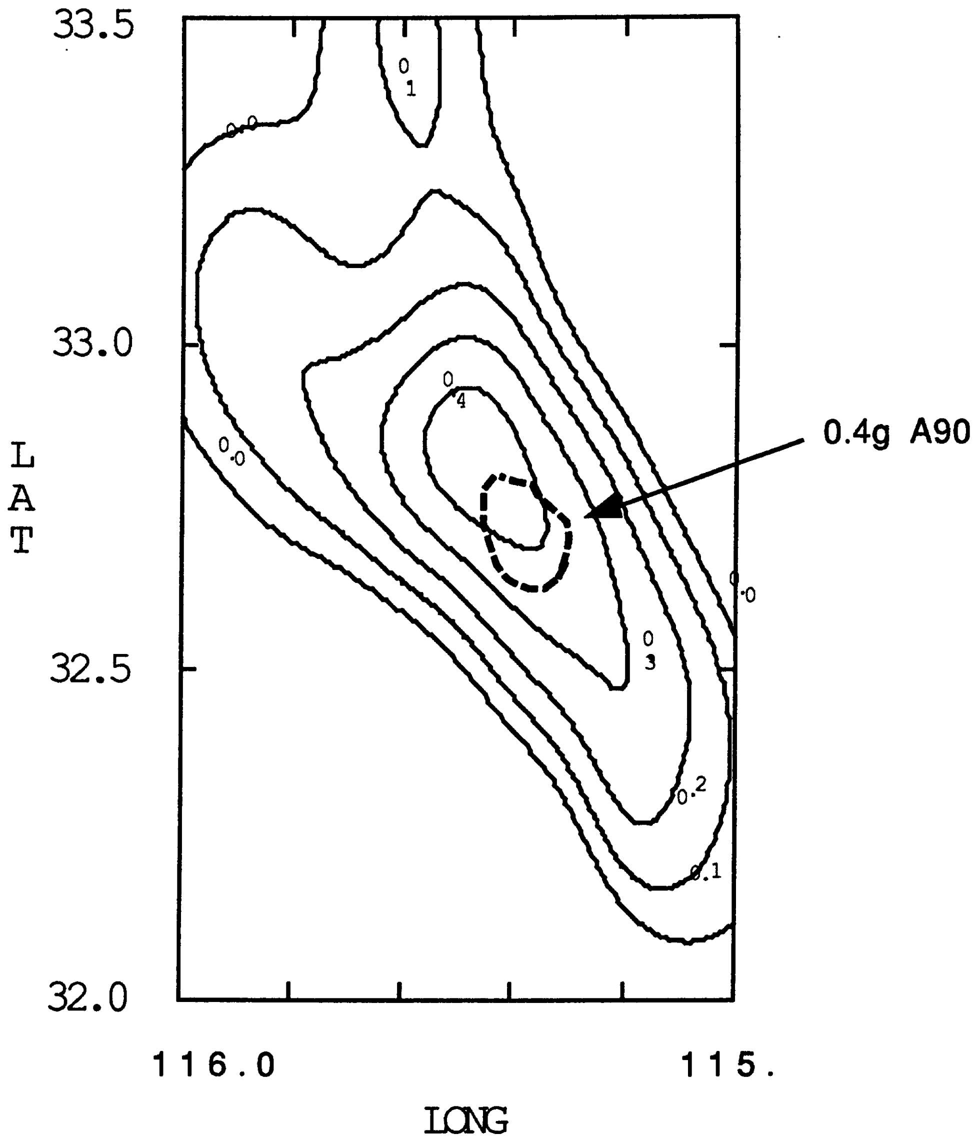

Fig. 5.- Isoacceleration map A0, Imperial Valley, California, earthquake of October 15, 1979 and isoacceleration line 0.4g from A90 isoacceleration map (Fig.3).

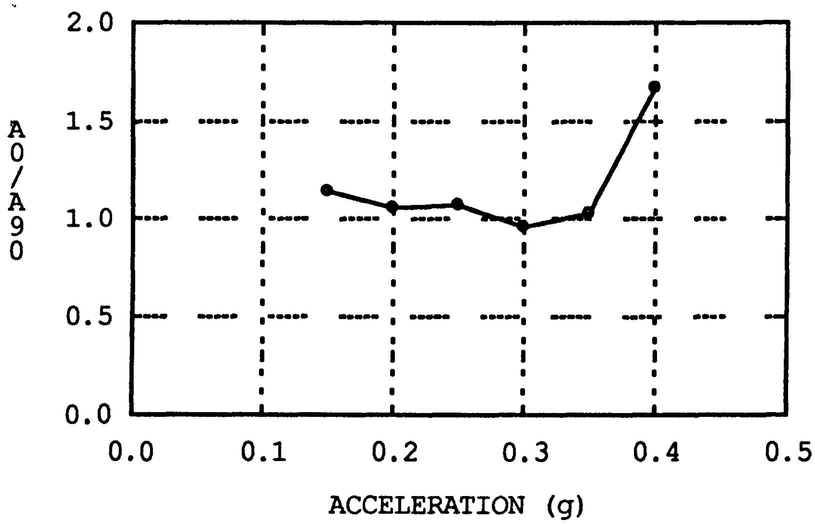

Fig. 6.- Ratio(A0/A90) of total area within equal isoacceleration lines.

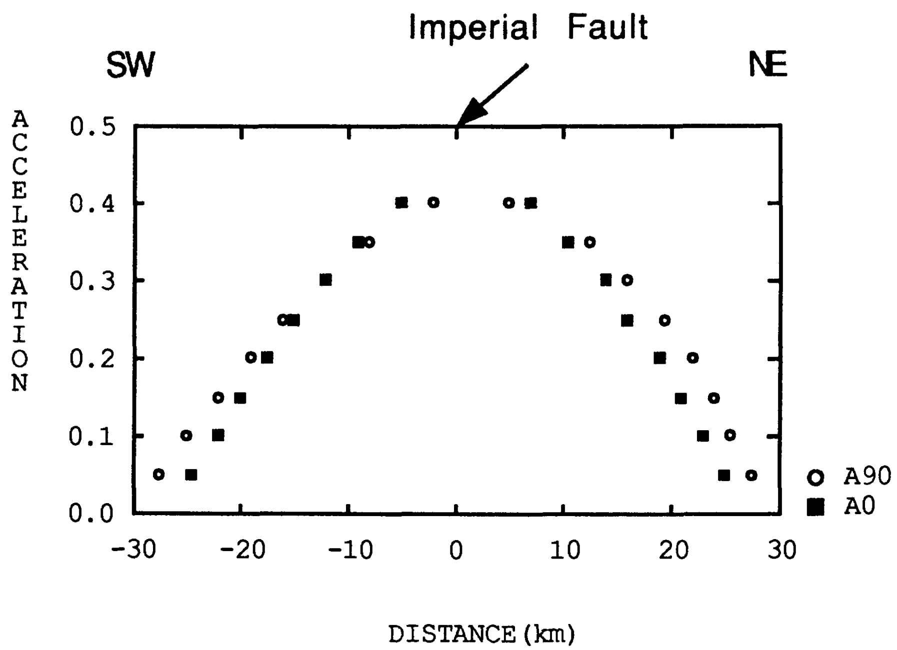

Fig. 7.- Acceleration attenuation perpendicular to the Imperial Fault break south of the Brawley fault.

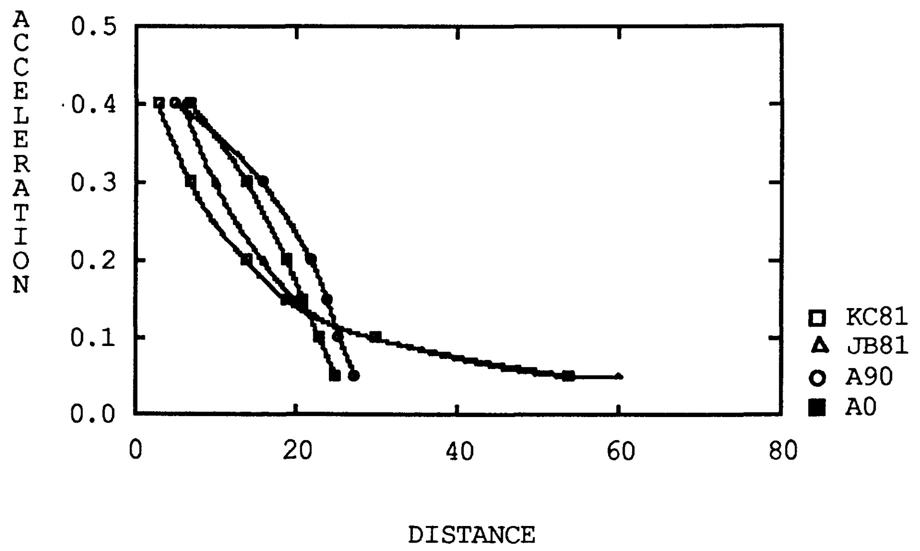

Fig. 8.- Comparison of acceleration attenuation A0, A90, predicted mean horizontal peak acceleration IV79 (Campbell,1981) and predicted 50 percentile horizontal acceleration M6.5(Joyner and Boore,1981).

BASIC PROBABILISTIC MODELS USED IN HAZARD MAPS

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The model used for the calculation of probabilistic ground motion maps of the United States prepared by USGS (Algermissen and Perkins, 1976; Algermissen and others, 1982, 1988) is based on the assumption that earthquakes are exponentially distributed with regard to magnitude and interoccurrence time and uniformly distributed in space with regard to source zones and source faults. The exponential magnitude distribution is an assumption based on empirical observation. The assumption of an exponential interoccurrence time is that of a uniform distribution in time, the so-called Poisson process, and is consistent with historical earthquake occurrence insofar as it affects the probabilistic hazard calculation. Large shocks closely approximate a Poisson process, provided a sufficient number of seismic sources are considered, while small shocks may depart significantly from a Poisson process. The ground motions associated with small earthquakes are of only marginal interest in engineering applications and consequently the Poisson assumption serves as a useful and simple model. However, in the western United States, there are sites for which the hazard is high, being dominated by frequent recurrence of large-magnitude earthquakes on a single fault source, and for which geologic evidence provides data for non-Poissonian occurrence models.

The usefulness of the Poisson process in the engineering analysis of earthquake ground motion has been known for a long time (see, for example, Lomnitz, 1974; a recent treatment of the problem is given by Cornell and Winterstein, 1988). In general, use of the Poisson process provides appropriately conservative values of ground motion for engineering purposes if sites of interest are affected by more than two sources of earthquakes (seismogenic structures). Sites in the United States are generally affected by more than one important earthquake source and for sites in the United States influenced by only one important source of earthquake, there is generally insufficient data to develop probabilistic models other than the Poisson model.

For the new series of maps currently being developed by USGS, we plan to use the Poisson model for most source zones throughout the United States. However, in those parts of the country where sufficient historical and paleoseismic data are available, separate take-out maps will be prepared using a suitable time-dependent model for the larger earthquakes (for example, a Weibull recurrence model for so-called "characteristic earthquakes"). Candidate areas for this kind of treatment include portions of the San Andreas Fault, western Nevada, the Wasatch Fault, and possibly Puget Sound and south central Alaska. An important source in the development of our time-dependent probabilistic models for California will be the recently published discussions on conditional probabilities for the occurrence of large earthquakes on fault segments of the San Andreas, San Jacinto, and Hayward Faults between the years 1988-2018, (The Working Group on California Earthquake Probabilities, 1980).

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The Importance of Geologic Conditions on the Level of Strong Shaking: Incorporation of Site Response in National Probabilistic Hazard Maps

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Several strong motion data sets have been recorded that clearly demonstrate the importance of geologic conditions on the level of strong ground shaking. These data suggest that significantly higher spectral ground motions can be expected at some sites underlain by alluvium compared to rock sites for periods above 0.1 seconds and ground shaking levels up to 0.5-0.7g.

The data from the 1985 Michoachan earthquake (Singh and others, 1988a; Singh and others, 1988b) show that the damaged zone in Mexico City experienced long-period ground motions (≥ 1 second) at sites underlain by unconsolidated lake deposits that were higher than nearby sites underlain by basalt by mean spectral factors near 10. Even higher factors were observed at another lake deposit site, although the effects were shifted to longer periods and did not produce damage to low-rise structures in that area.

The data recorded in Chile during the 1985 earthquake also demonstrate strong site effects (Algermissen and others, 1985; Askew and others, 1985). Records from stations at Llolleo and Melipilla showed spectral levels ranging from 4 to 10 times the levels recorded at rock stations Valparaiso and Quintay over the period range 0.2 to 4 seconds. The alluvium sites remained about a factor of 2 to 4 times above the rock sites from 0.04 to 0.2 seconds. Peak accelerations at the alluvium sites reached levels of about 0.6-0.7g while the records at the rock sites had levels in the range 0.16-0.25g. Another record at San Isidro (Algermissen and Campbell, written comm.), a site probably underlain by thin alluvium, exhibited spectral values 10 times greater than the rock sites over a narrow period range between 0.2-0.8 seconds. Peak accelerations at the San Isidro site were on the order of 0.5-0.7g for about 10 seconds.

Data from the San Fernando earthquake showed spectral site effects having mean values as large as 6 in the spectral band 0.2-6.0 seconds (Rogers and others, 1985). The recent Coalinga (Jarpe and others, 1988) and Whittier Narrows (Campbell, 1988; Bufe and others, 1988) earthquakes produced data that contain clear examples of increased ground motion due to site geology. Large peak accelerations, approaching 1g, have also been observed at sites underlain by alluvium in the 1980 Victoria, Baja California earthquake (Munguia and Brune, 1984); comparable peak accelerations were also observed at alluvium sites in the 1979 Imperial Valley earthquake, including one substantially higher recording that reached 1.75g on a vertical component instrument; these large values were partially attributed to site effects (Archuleta, 1982). Surface recordings of about 0.1g at a McGee Creek, California site underlain by alluvium are about a factor of 4 greater than those recorded by a borehole seismometer implaced in bedrock below the alluvium at 166m depth (Seale and Archuleta, 1988). Underground nuclear explosion recordings at the Nevada Test Site can also be cited as examples of strong shaking that demonstrate significant site effects (Murphy and others, 1971). Nuclear event recordings of about 0.5g reflected spectral site amplification (at about 10 Hz) of up to factors of 8 compared to nearby rock sites. This recounting is not complete; other important examples have been cited and discussed by Aki (1988).

In spite of the evidence suggesting that site effects are important, considerable controversy still exists regarding the magnitude of the effects, whether they are predictable, and the appropriate prediction methods. Resolution of these questions will require numerous strong ground motion recordings on alluvium and nearby rock sites and up-hole/down-hole strong motion recordings. These data are needed for a variety of alluvium types and a range of ground shaking levels. "Blind" testing of prediction methods, in the manner of the experiments underway at Parkfield (Tucker, written comm.) will be required to convincingly demonstrate their validity.

This problem is compounded by the complexity and range of site effects. It is unlikely that enough data will be available on a national scale to map local variations in site effects. Ground shaking levels, for instance, appear to be strongly controlled by the depth and shear-wave velocity of sediments, and these data are particularly difficult to obtain. Nonetheless, efforts should proceed to incorporate site effects in ground motion estimates for hazard assessment. Eventually, these efforts will guide the future collection of data that are relevant to the problem, leading to improvements in the data base.

In one straight forward approach, probabilistic maps would be developed that are based on attenuation of peak values for a limited number of generalized site types. For example, attenuation curves could be developed to include one or more categories of site conditions, such as "average rock," "thin soil," and "thick soil" conditions. Maps based on this type of generalization have the drawback that the maps are not site specific because their predicted values average the site response over a range of site conditions within each category. Nonetheless, maps developed on this basis might provide an indication of the magnitude and general characteristics of site response that would be a useful first order estimate of the ground motion hazard as a function of broad classes of geologic conditions.

In the long term, the most useful methods of accounting for site effects in predicted ground motions will involve the use of spectral values. Furthermore, prediction of rock spectra would be desirable in order to provide a base from which one could make site specific predictions based on either linear or non-linear models of soil behavior.

Although, ideally, one would prefer to produce probabilistic ground motion maps depicting ground motion parameters for sites underlain by rock, rock sites themselves commonly exhibit a site effect (Tucker and others, 1984) that can have substantial influence on ground motion levels (i.e., Pacoima Dam (Boore, 1972) and Griffith Observatory (Rogers and others, 1985)). These effects are due to the presence of thin soils and weathering and the effects of topography at some rock sites. Such effects can contaminate both the estimation of alluvium site response relative to rock and rock attenuation curves. Furthermore, the number of rock site recordings on which to base prediction equations may be too limited, leading to unacceptable statistical variance of the predictions. If probabilistic ground motion maps are produced for an "average rock site", and we wish to correct these maps to account for the effects of alluvium, then the site correction should be calculated relative to the same "average rock site" datum. Clearly, this requirement will be difficult to achieve in practice. If this requirement were achievable, however, the benefits of basing ground motion predictions on map values for sites underlain by rock are that the map values could be corrected for specific site conditions, particularly if the map values were spectral ordinates. In this scenario, rock maps would be produced and the user would apply corrections to the map values based on information available for his specific site conditons.

The largest percentage of strong motion data for the U.S. is from recordings of California earthquakes at sites underlain by alluvium. On the premise that attenuation relations should be based on the best data set, that is, the data set with the best distribution of magnitudes and distances and the largest number of data points, one could argue that national maps should be based on attenuation curves for an "average soil" site for California. These curves could then be corrected, as required, for differences in site conditions relative to the average site and regional differences in attenuation. Spectral maps would be the simplest values to correct to other site conditions. The first step would be the development of regression equations for a selected number of spectral periods using an appropriate selection of recordings from the collection of "average soil" stations. This spectrum, $\Omega(T; M, R)$, is assumed to be a function of period, T, for the parameters, magnitude (M) and distance (R). Next, one would construct spectral ratios of the desired site types (i.e., thin alluvium, thick alluvium, rock, etc.) to the "average soil" type. For example, let $`s_i^m$ be the spectrum recorded at the $m^{th}$ station $`S^m$ in category $`C$ for event $i$, and $s_i^n$ be the spectrum at station $S^n$ for event $i$, and $S^n$ is the $n^{th}$ nearby alluvium site selected from the data set containing all "average soil" types. Then, the mean correction factor $STF$ that defines the effect of site category $`C$ relative to the "average soil" type is given by

$$STF^{`C} = \frac{\left[\sum_{m=1}^{q1}\sum_{n=1}^{q2}\sum_{i=1}^{q3} `s_i^m / s_i^n\right]}{q1 + q2 + q3}$$

where $q1$ = the number of stations in the category $`C$ recording event i

$q2$ = the number of "average soil" sites recording event i

$q3$ = the number of events

The geometric mean might also be used, if appropriate. This equation represents the average ratio of all stations in category $`C$ to all stations in the "average soil" set, recording the same events and for all events common to both site types. Not all terms in this mean will be present because not all stations record all events, and not all stations in the "average soil" sample will be appropriately close to the stations in $`C$ category. Stations used in the spectral ratio must be at about the same distance and azimuth from the source in order to avoid incorporation of attenuation and source effects in the ratio. This technique would permit the computation of a mean rock spectrum by correcting the spectrum $\Omega(T; M, R)$ by $STF^{`C}$, where $`C$ in this case is the set of sites underlain by rock. This technique assumes that none of the sites used in the analysis have undergone substantive non-linear soil behavior. A mean rock spectrum obtained using this approach could be used to predict site specific behavior at any alluvium site using either linear or non-linear models.

As an alternative to this method, each spectrum in the average soil data base could be corrected individually to a rock spectrum using measured average site transfer functions for the site computed relative to nearby rock sites. Subsequently, the data base used in the regression is the set of "rock corrected spectra". The measured site transfer functions could be derived from strong motion or weak motion data or, if sufficient geotechnical data were available, the STF could be computed theoretically. Again, predictions of rock site spectra could be mapped and the mapped values corrected as required for site specific conditions. The data base required for this approach, however, may not yet be available.

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VIEWS ABOUT NEW GROUND MOTION MAPS FOR BUILDING CODES

by
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Need for new maps

I have for several years been concerned that the maps incorporated in today's building codes are based upon work done in the early 1970s. There is definitely a need to have them updated, and I am delighted that the USGS is committed to producing maps that might serve this purpose. ATC-3 attempted to break away from the concept of mapping only one parameter, and attempted to get across the point that one should deal with "effective" peak accelerations and velocities - but, partially because there was no precise definition for "effective" peaks and because the velocity-related map was not as soundly based as the acceleration-related map, the attempts were not successful. Now the time should be ripe to break away from old concepts and introduce new approaches to mapping.

What parameters to map

I do not have a preconceived answer to this question, and am here to learn the views of others. I am aware of a strong undercurrent of belief that we should be mapping constant probability elastic response spectra, but there are a number of issues that arise.

Presumably this means mapping spectral ordinates for a certain number of structural natural periods, and having an algorithm for constructing the entire spectrum from these few values. For how many periods must ordinates by mapped? Does the necessary associated algorithm already exist, or is there a need for extensive further R&D on this topic. From an Eastern perspective, there is special interest in response of structures having fundamental period of 5 to 10 seconds.

While an elastic response spectrum may be an adequate starting point for dynamic analysis, it does not suffice for the design of a large number of buildings - for many of which no dynamic analysis will be made, at least in the near future. For this near future, it must be possible to go from the mapped quantities to something like a lateral force coefficient that in turn is dependent upon the "ductility" in the structure. It is at this step that duration (or number of significant cycles) becomes an issue. There has been a fair amount of research related to this matter, some of which suggests that duration may not (except in rare circumstances) be as much of an issue as thought. However, I suspect these matters are far from settled and there is a vital need for further research - at least for careful interpretation and synthesis of completed research.

This last matter brings up the question of timing. By 2000, we may have quite a different approach to design. Dynamic analysis likely will be more routine, and we may then be using a 2-level approach to design - checking first for elastic behavior and acceptable distortions for the "probable" earthquake and then for safety during some "maximum" earthquake. However, it is unlikely that such changes will occur by the next round of code revisions. Should we focus on the short-term need for better maps, or leave the existing maps as they are in the next revision and focus on some long-term goals?

The soil/rock/microzonation issue

One question concerns maps for the country as a whole. I often hear that we should map ground motion parameters for rock. This would be OK if we could really be confident about transferring from rock to near surface conditions, but I am not at all sure we are. Moreover, the concept of mapping some motion parameter applicable to a 1000-foot depth is not likely to fly for building code purposes. It certianly is essential to be very clear to what soil-rock conditions the mapped parameters do apply. I would like to use a "standard" or "common" condition that will vary from region to region - in some places being rock and in other places being soil. I am not sure this is any more ambiguous than the meaning of "rock" in different parts of the country. Even if we could define "rock", do we really know the motions on "rock" in all parts of the country?

A second question concerns accounting for local soil/rock/topographic conditions. The current approach is to leave this problem to the engineers for each individual case. An alternative is to prepare maps for small regions taking in account such effects. I feel it should be possible to follow this latter alternative, but we still lack a strategy that is politcally and technically palatable.

Efforts at NCEER

I am here because NCEER is concerned about hazard mapping and has assigned me funds to hold a workshop focussing on just the same questions that we are here to discuss.

NCEER is not clear as to just what it wants to do about mapping. My own personal views are that NCEER should have the capability to make ground shaking hazard assessments, at least to provide suitable responses to questions raised by the engineers associated with the organization. It likely makes sense for NCEER to undertake mapping of the hazard for some small region; certainly this endeavor would help focus the work of its researchers in seismology. However, I hope that a good working relation can be established between USGS and NCEER such that NCEER feels it unnecessary to get deeply into the mapping business.

For the present, the point is that I have money that can be used to supplement the efforts at this meeting to recommend "what should be mapped" - and I hope to learn how best to use these funds.

NEW APPROACHES TO REPRESENTING SEISMIC HAZARD INFORMATION FOR BUILDING SAFETY REGULATION

by
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The current mapping process has yielded maps of utility and importance. To understand the utilization of seismic hazard maps, we must recognize that the interests of different users of seismic hazard maps can be quite different. The regulator is concerned with very large numbers of buildings and is satisfied with statistical measures of adequate building performance. The occupant is concerned with life safety in the building and is unimpressed with the argument that only the building he was in was badly damaged; the owner is concerned with economic continuity; and, the designer is interested in liability control. It would be surprising if one approach to representing seismic hazard would serve all these different interests. Yet this is precisely what is done: one map is used for a variety of different purposes, not-with-standing the assumptions made by the developers. There have been many development that suggest it is now time to assess other possible approaches to processing available scientific information and representing seismic hazards. This brief note will explore a few issues and propose some approaches to representing the hazard to begin the dialog leading to a new generation of hazard maps.

There are several observations that set the stage for the coming proposals. The first is to note the way in which seismic hazard and risk problems are framed. An analog of earthquake risk is gambling, where the gamblers are forced to continue to play the game until they are wiped out. There are two ways to approach analysis of such a problem. From the point of the casino (community at large), it is satisfactory for some players to go broke and others to win large sums, as long as the expected value over all the players is in their favor. The designer and owner, on the other hand, have a building and are concerned about its performance; in gambling the corresponding problem is termed the ruin, or zero crossing, problem since when his bankroll is gone he can no longer play the game (corresponding to building failure). Statistically these are substantially different problems. The first problem is a straight forward one of expected values where we can substitute averages over time for one gambler for averages over all the gamblers; it is easily assessed with simple mathematics. The latter is more difficult and leads to results, like the arcsine law to determine the time to zero crossing, that are far from simple either conceptually or mathematically. The dilemma is that so far the problem of seismic hazard (and risk) mapping has only been posed for the large group, appropriate for administrative use in codes (casino), not for the individual building (gambler).

A second observation is the divergence between current map values and apparent facts. We are told that there is a high probability of an 8+ earthquake near San Bernadino in the next 20 years and the Joyner-Boore attenuation formula (or any other you prefer) predicts that the mean accelerations for some sites are .6g and higher, but the zone map value given by the "map" indicates a 10% probability of having an acceleration over .4g in the next 50 years. Clearly these pieces of information at at odds and need resolution, if the maps are to be given credence either within the profession or public policy process. (The escape of arguing that the zone coefficient is not an acceleration is a semantic game, not a resolution of the dilemma.)

Third, the current presentation of zone or ground motion maps are based on the assumption that a uniform approach is appropriate to the entire country. There are many issues of geology, seismology and tectonics that need to be addressed in determining whether the approach appropriate to one area (California) is also appropriate to others (whether east, northwest or intermountain areas). And there are even more differences in construction practices among regions that further challenge the notion of using the same approach throughout the country, since the robust seismic design parameters for different construction styles are likely to be different.

Fourth, the current strategy of map preparation is based on probabilistic methods developed to incorporate site accelerations from many possible earthquakes and statistical variations in response. It is neutral, treating all equal acceleration values the same, regardless of whether they arise from small earthquakes or large ones. The seismic hazard equivalence at a site of a .4g peak acceleration arising from a magnitude 4 and a .4g acceleration arising from a magnitude 7 earthquake is clearly not a consistent way to treat acceleration for building performance. Such differences are also observed in earthquake policy questions, where the focus of our public policy is on large losses in single events, not on large numbers of small loss events of comparable total. Economists have addressed this problem by developing expected utility theory. A utility function of the value under consideration, sometimes including other parameters or characteristics, is used rather than the value itself. But this still has difficulties, and the methods of decision theory (e.g., fault trees) and systems theory (e.g., minimize maximum regret criterion) have been developed to address these problems. It is not surprising, then, that the simple PRA method used in current seismic hazard mapping leave the users so unsettled.

An example is instructive of the difficulties encountered in using PRA analyses that value all contributions equally: at a specific site in Southern California the 10% probability of exceedence in 50 years acceleration for a site is .36g when the maximum earthquake considered in the analysis is of magnitude 5; it increases by 20% to .43g when earthquakes between 4 and 5 are added to the analysis. The mathematics are correct: it is the result of the uncertainty of ground motion attenuation combined with the high frequency of smaller earthquakes, not-with-standing the lack of any observational damage to competent buildings from earthquakes in this lower range. Most engineers certainly would consider the problems posed by large earthquakes to dominate concern, yet current methods make no distinction between the peak ground motions that result from substantially different magnitude earthquakes. Now, this can be "fixed" by excluding the lower level earthquakes or limiting the attenuation statistics (or ignoring these statistics altogether), but they compromise the integrity of the formalistic arguments for the approach in the first place and smack of fudging the results. A weighting function, corresponding to the economic notion of utility can be easily developed, given that agreement can be reached as to the importance of site accelerations from different magnitude earthquake (and/or source durations, etc).

Different approaches to processing seismic exposure information to yield hazard representations (maps) useful to design and regulation need to be developed, evaluated and considered for use. To initiate discussion, four different approaches are presented, staring with a modest change from current practice.

1. MAPPING COEFFICIENT PROBABILITIES The 1988 UBC prescribes three zone coefficients (.2, .3, and .4). Thus, for administrative purposes the seismic zonation map only needs to specify 4 (including the category below .2) different zones. The current approach to mapping picks a probability of exceedence in a given period (10% in 50 years) and then maps contours of constant acceleration values. It is natural to map acceleration value contours with uniform probability of exceedence if acceleration is a variable used in design. However, since there are only 4 categories of acceleration related zone coefficients used, then it seems more reasonable to pick the acceleration value (or some other parameter or processed value, see above economic discussion above) and map the contours of constant probability of exceedence. This will make the process of assigning probability values more transparent to the practitioner and code official and matches better the safety assessment process. (The importance factor I is used as a multiplier of the zone coefficient in the base shear equation as a means of increasing the effective ground motion to provide conservatism in response, without reference to the probability of exceedence not-with-standing its purpose. Thus, it may be useful to add .5 (for 1.25 times the largest value, .4) and .6 (for the old Importance Factor value of 1.5) values to accommodate the importance factor practice.)

2. PERFORMANCE MAPS The Blue Book, ATC and UBC maps reduce the problem of specifying design coefficients to a few very broad categories. The user of these maps is given little in the way of cause-effect reasoning on how the map was obtained and most do not understand its origin; probability, much less probabilistic hazard or risk analysis, is not a widely understood subject among practicing engineers, building regulators or public officials. Further, it provides no opportunity for revision when new information is available or different performance criteria required.

At the root of the difficulties in interpretation of probabilistic seismic hazard analyses is that a number of fundamentally different types of physical uncertainty are combined:

- Uncertainty in ground motion at a site for a given earthquake's occurrence.
- Uncertainty in timing of major earthquakes that are known to have occurred one or more times along known features and are likely to recur.

- Uncertainty in whether a known geologic feature can be active, and if so, with what statistics.
- Uncertainty in assigned creep rates, especially since few are measured and there is little indication from data whether they are piece-wise constant or episodic.
- Uncertainty in whether all the features that could be sources are known and/or identifiable.

Current methods of probabilistic hazard analysis combine all of these uncertainties in one grand estimate. The dilemma is that the user has a hard time sorting out what portions of the hazard are most important, especially since they may not be knowledgeable of the underlying disciplines, and thus tend to down play the results.

It is proposed that we recognize the inherent differences in the types of uncertainty that exist in estimating hazards as alluded to above, and sacrifice mathematical purity for understandibility by partitioning the hazard specification process into 4 distinct steps. Note that acceleration could be replaced by any other parameter.

Step 1 -- Ground motion for known, major earthquakes. The characteristic earthquake of faults for which there is historic evidence of major earthquake occurrence would be considered on a deterministic basis to occur within the lifetime of the structure; there are few of these earthquakes in California and probably none in the east. This reduces the problem of ground motion characterization to one of determining the confidence that a given value would not be exceeded during the earthquake. In effect, the probability of occurrence of the earthquake has been suppressed and all the variability reduced to the ground motion response to the event. This seems reasonable since we are sure that the characteristic earthquake will occur and while its timing may be in doubt, the likelihood is that it will occur during the structures lifetime. This hazard can be mapped, or a simple formula can be used for given, mapped faults and moment magnitudes of events. This analysis gives a value of ground motion (say acceleration) a_1 with confidence of non exceedence of C.

Step 2 -- Regional sources. The balance of the identified sources are lumped into a regional source for earthquakes above the threshold value used in Step 3. Seismic catalogs give estimates of the regional activity through Guttenberg-Richter type relations. The problem with this type analysis is that it applies to regions not individual sources or small areas. An individual building is located within this regional source at a fixed distance from a possible causative feature. Since the uncertainty associated with the features that could give rise to this event are both in whether they are active and the degree of activity, we lump these uncertainties in a probabilistic analysis to determine the confidence that a given ground motion parameter, a_3, is not exceeded with confidence C. Since the closest features location (d) to the building is known, the assessment is done for a regional source with an excluded circle of radius d. The possible sources would be identified on a map so building locations could be easily located. The analysis would lead to a few curves for different regions that could be used to determine the appropriate value of a_2. An alternative would be to specify a standard distance, s, that is assumed, unless a geologic investigation demonstrates that a different value can be used. This gives a direct way to incorporate geologic investigations into the hazard analysis.

Step 3 -- Mobile earthquakes. There still remains the possibility of small to moderate earthquakes that can occur on unidentified or identifiable features. These are most likely small events, say of magnitude 6.0 or lower, varying with region. Noting that they are quite frequent on a regional basis and that the purpose of building regulations is to provide a minimum level of safety for likely events, the statistics of ground motion for a magnitude 6. event at a prescribed distance (say 5 kilometers) are developed in a single curve. The ground motion a_3 that Nhas a given confidence of non-exceedence is determined.

Step 4 -- Determining the design parameter. The three values a_1, a_2 and a_3 are distinct representations of the possible ground motions that could occur in the three distinct types of situations. It is proposed that the ground motion parameter selected for design be the maximum of these three numbers, all determined for the same confidence of non exceedence. While this selection rule may sacrifice some mathematical niceties, it has the advantage of being intuitive and straight forward.

Given these values, several maps could be drawn to aggregate the results of the analysis (for the default situation of no geologic study) characterizing the ground motion for different levels of confidence (say 50%, 84%, 95%). Specification of the confidence of nonexceedence could replace the current Importance Factor for specifying base shears. One of the features of this approach is that in Steps 1 and 2 the expected lifetime of the structure is immaterial, since the event is presumed to occur within the lifetime of the building. Step 3 requires specification of a lifetime, which we may wish to standardize at a few simple values (say 50, 100 or 250 years); this posses little difficulty and is not expected to cause major differences.

An advantage of a process such as this is that new information on the characteristic earthquake of a given feature, on identification of active or inactive features and on developments in strong ground motion attenuation relationships can be incorporated without forcing a complete reanalysis as required by current probabilistic hazard analysis methods. Further the analytic method does not obscure the intellectual process.

3. LINEAR MODELS FOR THE MAPPED PARAMETER The third alternative is based on research results from the aggregation of expert opinion and the making of judgments under uncertainty. One of the basic themes developed and supported by extensive research and experiments is that experts are good at picking out the right predictor variables and at coding them in such a way that they have a conditionally monotone relationship with the criterion, but experts are bad at integrating information from diverse and incomparable sources. A large body of research indicates that simple linear models, where the experts determine both what variables are important and the their relative weights, out perform the experts in making judgments under uncertainty in virtually all cases. Certainly the problem of determining what parameter adequately characterize seismic hazard for building design purposes falls into this category, if by no other argument than the observation that it has not been done in over 30 years of trying. Variables that are often discussed as being

important in determining the performance of buildings include: peak acceleration, peak velocity, peak displacement, spectral shape, duration, energy, and number of cycles of strong motion. In this approach, a linear combination of these variables would be used to determine the specific parameter with the weights determined by experts for different classes of structure and performance expectations. Probabilistic methods would then be used to determine what value should be assigned. This would vary for different types of structures: it is expected that the linear model for brittle structures would be different from that for limber ones; steel different than concrete; eastern concrete frames from their western counterparts, etc. But there are likely to be only a few such categories, not a lot. As a simple example, suppose that for a class of buildings the peak acceleration and duration of strong motion are considered, as measured by the source duration, and that design to a higher acceleration level can accommodate increased duration. Then the design acceleration, a', could be given in terms of the source duration, t, a reference duration, tr, and the peak ground motion, a, as $a'=a(t/tr)^{\frac{1}{2}}$ where abs(t-tr)>=tr/2, a'=a otherwise (a log linear relation; values for illustration only). In such a formulation the design importance of equal ground motions from different magnitude earthquakes would be treated differently, with the greater magnitudes receiving greater importance.

4. AI APPLICATIONS The last observation is that there are many elements of the seismic hazard characterization that are not easily or properly quantified. One need only look to the specification of slip rates for faults to observe that we are specifying values (and sometimes ranges) on the basis of opinion (guesses?) not facts, but processing the results as if they were facts. And the problem is further complicated in that causative relationships in tectonic are not well characterized, much less susceptible to quantitative description: determination whether a particular feature is seismogenic or not is judgmental not quantitative. Much of the discipline of artificial intelligence (specifically expert systems) has been developed to address these types problems and offers a number of interesting possibilities for development of different mapping strategies. These observations suggest that it is appropriate to investigate using artificial intelligence methods to assign zone coefficients.

WHAT SHOULD BE MAPPED

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What should be mapped? Something that is useful for design purposes and is also physically reasonable and correct. This sounds like a simple and easily reached objective. Unfortunately recent mapping efforts and recent code changes show it to be a difficult problem. Maps estimating 10 percent in 50 year exceedance probabilities in California with peak values of 0.90g and with large areas exceeding 0.60g together with a new UBC zoning map showing no site in California with Zone 2 point out both the extremes and the difficulties of the code process.

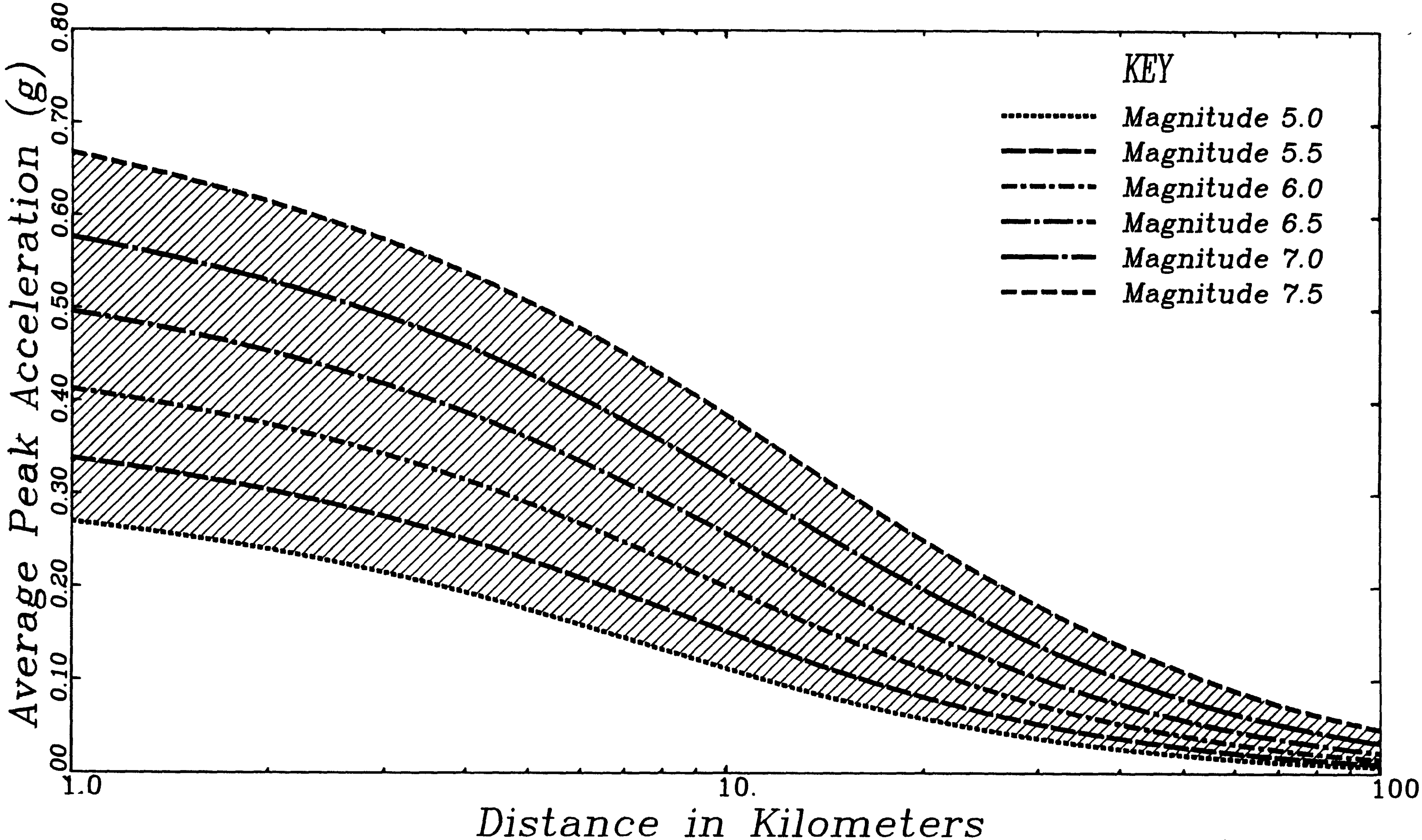
It is also important to realize what a code is expected to represent. It is a document which when adopted carries the legal requirement that it be satisfied. It is a minimum, or in the vernacular sense, a standard that represents the lowest common denominator. It is not a design manual which tells how to successfully design an earthquake resistant structure even though it is sometimes treated as such. It is a document used by building officials to check design calculations. If we recognize these limitations we are forced to conclude that any quantity mapped for code use must be very simple to use. ATC3-06 made a major step by suggesting that 2 zoning maps be used to represent ground motion characteristics. Subsequent steps have not followed through with this even though the new UBC map is entirely based on ATC3-06 results with politically motivated alterations.

Another aspect of mapped quantities is the perception of the lay person, or the uninformed technical person from another discipline who does not understand how the code was developed or how it is used. Structural engineers have been accused of being deceptively dishonest for using a lateral force factor which has units of acceleration and a value of about 0.1g when it is "obvious that motions recorded in an earthquake are many times larger." The new code equations and maps were a partial response to reduce misunderstandings arising from the misconception.

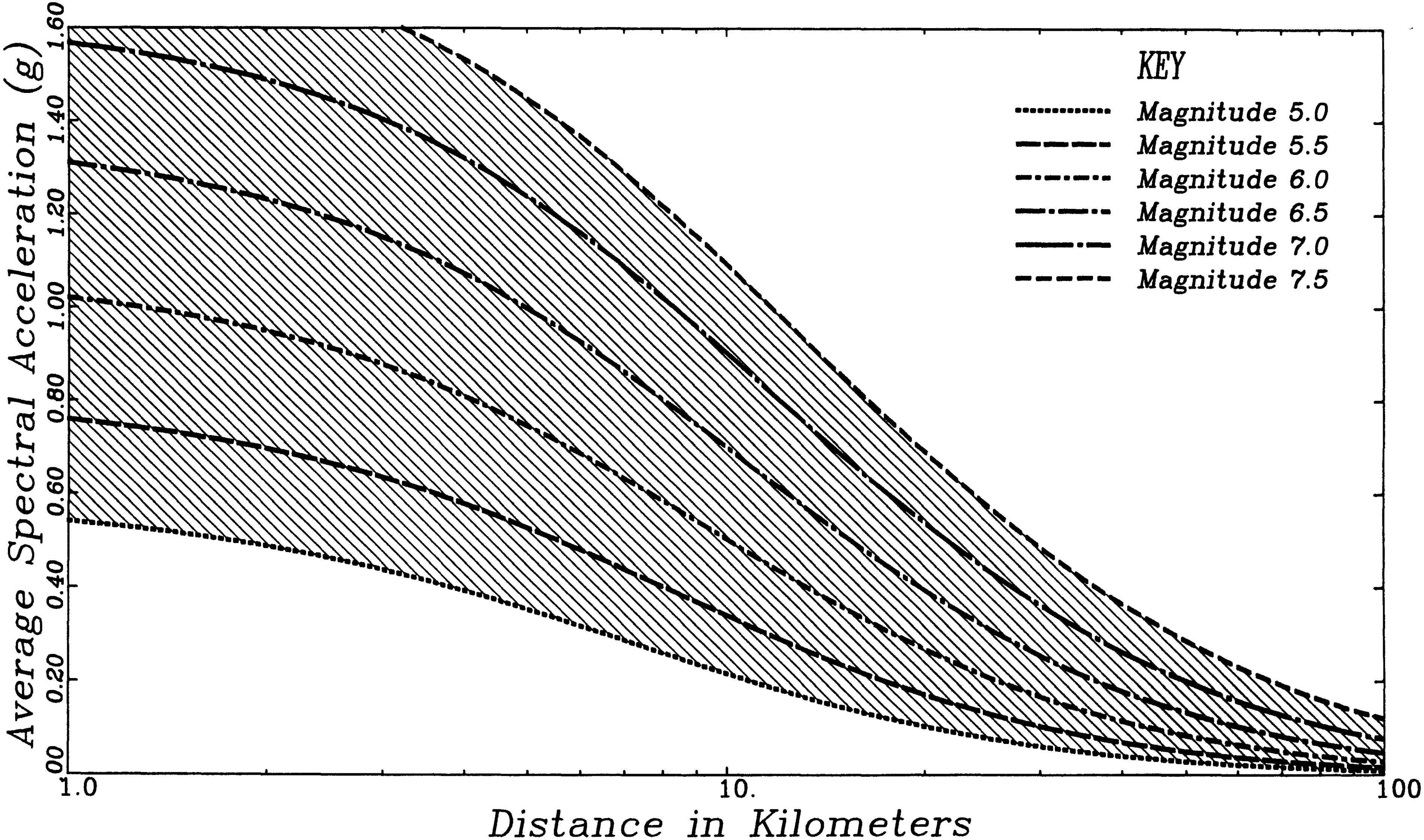
The quantity which has been most widely used to produce maps to this time is peak acceleration, contrasted to effective peak acceleration (EPA). Peak acceleration is a quantity which is one of the poorest means of discriminating between sizes of earthquakes and their damaging potential. Hanks and Johnston have argued that peak acceleration is largely magnitude independent. A significant step away from the mapping of peak ground motions towards mapping quantities of true structural significance has been made in New Zealand. Their new design standard uses maps based on a response spectral value. The value they have chosen is the response spectral acceleration at a period of 0.2 seconds. As an aside, were we to adapt this approach in a similar way to our present code we would have a maximum mapped value of 1.0g (1.0 = 2.5 x 0.4). While I believe the choice of spectral accelerations at 0.2 g is not the optimum value the move away from describing ground motions by peak acceleration is a very positive one.

Spectral attenuation equations developed using a consistent approach with scatter included as a parameter are now available in the literature from several different researchers. These permit the application of probabilistic hazard procedures to develop uniform risk spectra which offer the potential of mapping any spectral parameter if such a quantity should be deemed desirable by the more experienced structural engineer. Should such a procedure be recommended the relationships used for the map development should be based on relationships which have had a period of successful use by the consulting practitioners rather than some relationships developed especially for the mapping effort. The use of a consensus relationship for peak acceleration and especially spectral acceleration values would be a sound move for both technical and "egotistical" considerations. Examples of such "consensus" relationship for peak acceleration and spectral response acceleration at 5 percent damping for periods of 0.3 and 1.0 seconds are attached.

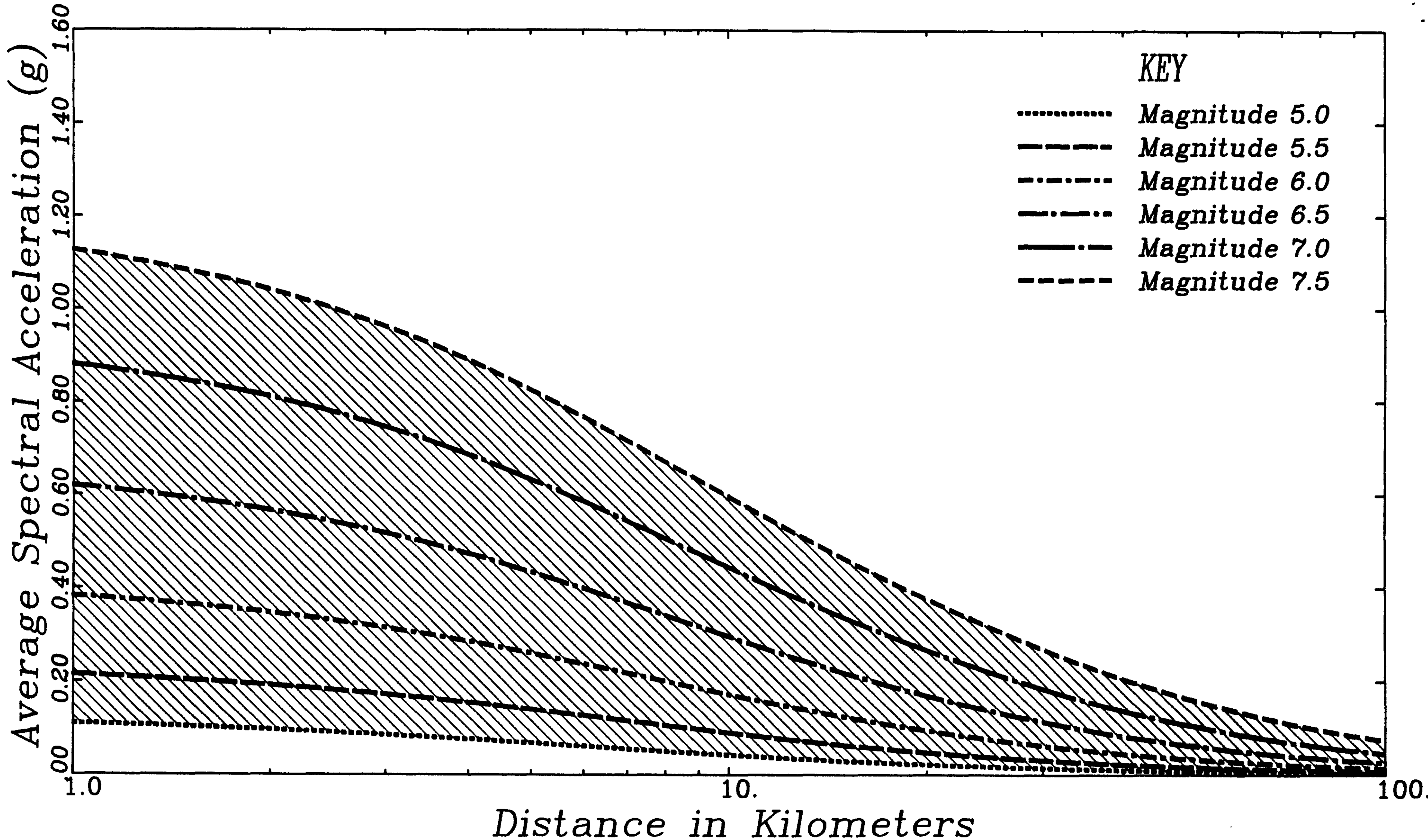
As a concluding comment I would like to point out that there is a considerable need for cooperation between the ultimate users of any potential mapping and those who would develop the maps. Without such a consensus there will be little to gain from the effort expended. I hope that the outcome of this workshop will be a program to prepare for a series of more specialized workshops to gain the necessary national consensus of both what is needed and how those needs may be best satisfied.



Acceleration attenuation relationship average curves. Based on equations by Campbell, Crouse, Idriss, Joyner et al, and Sadigh.



0.3 second period spectral acceleration attenuation curves.
Equations by Campbell, Idriss, Joyner et al, and Sadigh.



1.0 second period spectral acceleration attenuation curves.
Equations by Campbell, Crouse, Idriss, Joyner et al, and Sadigh.

STRUCTURAL ENGINEERING SEISMIC DESIGN PARAMETERS

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The primary end use of ground motion maps is in the structural design of structures, buildings, systems and equipment, and life line systems. Another use is in land use planning.

The seismic-resistant designs of most buildings and structures are based on ground motion parameters presented in building codes. These parameters or factors are used by engineers, architects, code enforcement officials, and city and regional planners to ensure that facilities within a jurisdiction are adequately designed to resist earthquake motions. Because of the many people involved in the design, construction and code enforcement process, code provisions must be reasonably straight forward and simple, and not overly complex or sophisticated. With these factors in mind, the following is offered:

1. The seismic response of a structure is dependent on the intensity, frequency content, and duration of strong ground motion during an earthquake. Currently, equivalent lateral static force is used for seismic design for most buildings and structures. Dynamic analysis is used for complex, irregular, important or essential facilities. A few structures are designed in accordance with the results of time history analyses.

   Consideration is also given to the underlying soil by using a soil factor or for more complex or essential facilities, soil structure interaction analyses are made.

2. For code provisions, the following parameters would be useful:
   a. Maps based on effective peak acceleration (EPA) rather than peak ground acceleration (PGA). Procedures for calculating EPA are given in the ATC 3-06 Commentary and in papers by Newmark and Blume.

b. Duration of strong ground motion is very important to the degree of structural damage sustained by a structure. Response spectra plots of the peak responses of damped single degree of freedom systems indicate the amplification of response, but give no indication of duration. The number of peak or near peak responses are most important. Perez and Blume, among others, have published papers on development of response spectra with a third axis, time; i.e., acceleration, period or frequency, and time. The number of cycles of peak or near peak responses at each different period value can be readily discerned.

c. The variation in acceleration and pulse shape (i.e., "fling" phenomenom) with proximity to active faults would be useful, especially for the design of certain types of structures and systems, such as seismic isolation systems.

d. Median or mean curves should be provided together with one sigma curves for use with special or essential structures. Most buildings would be designed for median or mean curves.

e. The variation of acceleration and or response spectra with soil type (i.e., soft, stiff, and rock plus a fourth soil type analogous to Mexico City) is currently considered by using a soil-type factor. Maps for each of the three or four soil types would be very helpful as the current approach is not very realistic.

f. Mapping of peak velocity will be of value in the future. The use of such curves in design will require an extensive educational effort.

3. It is extremely important that the ground motion maps as they are developed be reviewed and discussed with the potential users, primarily the structural engineering designers. I would suggest that an Advisory Committee of structural engineers be appointed to work with USGS and make suggestions as appropriate so the final maps will be as useful as possible.

PROBABILISTIC MODELING AND WHAT I NEED FROM THE USGS

by

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It is essential that no matter what the parameters are that are selected for the USGS mapping program that we have estimates of the mean and the coefficient of variation of the parameters. An additional item that is needed would be the probability density function for the parameters.

It is now possible to obtain this information on a site specific building project for:

a. maximum (or EPA) ground acceleration for a design life of 50 years.

b. maximum spectral acceleration for 5% damping for a design life of 50 years.

Therefore, a USGS seismic mapping program that maps these two parameters would be the minimal expected research effort.

The 1990's will be the decade of nonlinear dynamic analysis in structural engineering. The nonlinear computer software now exists. Therefore, USGS must provide a library of near field and far field time histories for all seismic zones.

BIOGRAPHIES

S. T. ALGERMISSEN is a Supervisory Geophysicist in the Branch of Geological and Risk Assessment of the U.S. Geological Survey. A specialist in earthquake hazard mapping and risk (loss) assessment research, both in the United States and internationally, earthquake ground-motion maps developed by him have been used in building codes in the United States since 1970. He has participated in several UNESCO and UNDP projects as a consultant and was principal investigator in a number of earthquake hazard assessment projects in Latin America, Southeast Asia, Europe, and the Near East. He is former Director of the Seismological Society of America and the Earthquake Engineering Research Institute.

BERNICE K. BENDER is a Mathematician in the U.S. Geological Survey's Branch of Geologic Risk Assessment. Prior to entering the USGS in 1979, she worked as a mathematician with NBS and NOAA for 20 years doing numerical analysis and scientific computer programming. During that time she wrote the original computer program used by the USGS for mapping probabilistic earthquake ground motion hazard. Since entering the USGS, she has developed increasingly sophisticated computer programs for seismic hazard analysis. She has published frequently in the bulletin of the Seismological Society of America on various topics dealing with the mathematics and modeling or probabilistic ground motion hazard analysis. She has served as a consultant and reviewer for the Nuclear Regulatory Commission and Bureau of Reclamation.

MEHMET K. CELEBI is currently Research Civil Engineer in the Branch of Engineering Seismology and Geology at the U.S. Geological Survey in Menlo Park, California. His prior professional experience includes: assistant professor, associate professor of civil engineering at Middle East Technical University, Ankara, Turkey, from 1969-1977; research engineer at the University of California, Berkeley, from 1971-1973; engineering specialist at Bechtel Corporation from 1978-1979; principal engineer and technical consultant at EDAC from 1979-1981; professor (tenured) of civil engineering at San Francisco State University from 1981-1985; and his current position as research civil engineer since 1985.

Dr. Celebi, in his positions as research engineer and professor, has conducted research on dynamic testing of structures and components, analyses of structures, analyses of earthquake response records of structures and site-response studies. In his current position, Dr. Celebi is the project chief for seismic instrumentation of structures and conducts related researches.

NEVILLE DONOVAN is a partner in Dames & Moore, with whom he has been associated for over 25 years. His graduate education which led to the Ph.D. degree specialized in the fields of structural and geotechnical engineering. Starting over 20 years ago, his professional activities extended into the area of earthquakes and the estimation of the potential ground motion hazard for use in the design of structures. He was an early developer of the application of probabilistic approaches in the area of earthquake hazards. Donovan has been an active participant in code development and was chairman of Task Group 1 with responsibility for ground motion mapping and soil effects in the ATC3-06 research effort. Since that time he has continued with committee work that has led to the adoption of many of the recommendations of the ATC3-06 results in the 1988 Lateral Force Recommendation of the SEAOC and the 1988 edition of the Uniform Building Code.

He has published over 60 papers with emphasis on ground motion development and the application of probabilistic procedures in the field of engineering seismology and earthquake engineering.

GARY C. HART is Professor of Civil Engineering at the University of California, Los Angeles, and President of Englekirk and Hart, Inc. in Los Angeles. Dr. Hart is a member of a) the SEAOC Seismology Committee and b) the Executive Committee of the US-Japan Cooperative Masonry Research Program. He is cochairman of the 4th U.S. National Earthquake Conference and current President of the Los Angeles Tall Building Structural Design Council.

WALTER W. HAYS is Deputy Chief for Research Applications in the U.S. Geological Survey's Office of Earthquakes, Volcanoes, and Engineering (OEVE). Since 1977, and after 16 years as an educator and a research engineering seismologist, he has been responsible for fostering research applications and loss reduction throughout the United States. On behalf of UNESCO, he participated in earthquake engineering programs in Algeria and Jordan. Through USGS'S international activities, he contributed to scientific programs in Spain, Italy, Japan, China, Argentina, Switzerland, Austria, and the Soviet Union. He participated in the formative phases of the International Decade of Natural Disaster Reduction. A former Director of the Earthquake Engineering Research Institute, Dr. Hays chairs its Committee on Continuing Education, which has worldwide activities. He has published more than 100 papers, books and reports.

JEFFREY A. JOHNSON is currently President of Jeffrey A. Johnson, Inc., Westlake Village, California and chairman of the geotechnical subcommittee, SEAOC. Dr. Johnson is an applied seismologist and engineering geologist who has been involved in geologic and seismic studies in the United States, Central and South America, the Middle East and Japan since 1969. His educational and research interests have been devoted to the understanding of seismic and non-seismic geologic hazards and their potential effect on engineered structures. Dr. Johnson has been involved in the technical and political aspects of siting and design of major facilities in seismic regions of the world including liquidfied natural gas facilities in California and Alaska; nuclear power plants in the United States; major lifelines facilities including 500 kv transmission lines in California; development of seismic design parameters for the Metro Rail Project in Los Angeles, and the SOHIO midcontinent pipeline project from Long Beach to Midland, Texas; major computer facilities in California and Alaska and hydroelectric projects in South America.

Dr. Johnson has also conducted research on major earthquakes around the world including the Tokachi-oki, Japan 1968, San Fernando, California 1971, Managua, Nicaragua 1972 and Imperial Valley, California 1979, and worked with EERI on the original geotechnical plan to maximize learning from future destructive earthquakes. In addition, he visited Rio Blanco County, Colorado in May of 1973 for a site evaluation study for the purpose of placing instruments to record motion resulting from the Rio Blanco Nuclear Blast.

As an instructor at California State University, Northridge and UCLA, Dr. Johnson has taught courses in geology, environmental geology and earthquake engineering. He also conducted studies on the secondary effects of ground shaking for cooperative projects with various counties in California as a consultant to the California Division of Mines and Geology Duties included developing geotechnical maps depicting areas prone to liquefaction and differential settlement.

WILLIAM B. JOYNER is a geophysicist with the U.S. Geological Survey. He has been engaged in research in engineering seismology since 1970. His work includes papers published on the subjects of site amplification, nonlinear site response, attenuation relationships for ground motion, and predictive maps of ground motion.

EDGAR V. LEYENDECKER is a Research Civil Engineer with the U.S. Geological Survey. His current work includes studies in structural vulnerability and acquisition and analysis of damage distribution data. Prior to joining the USGS, Dr. Leyendecker was with the National Bureau of Standards (NBS) for over 17 years. At the NBS he was a supervisory structural engineer and head of the earthquake engineering group. He has been particularly active in improvement of seismic design criteria through his effort with the private sector's Building Seismic Safety Council and the Federal Government's Interagency Committee on Seismic Safety in Construction.

DAVID PERKINS is a research geophysicist for the U.S. Geological Survey in Golden, Colorado, in the Branch of Geological Risk Assessment. Since 1971 he has been involved in research on earthquake statistics and the development of techniques for assessing seismic risk in terms of probabilistic ground motion. He has served as a consultant for the Nuclear Regulatory Commission, the Bureau of Reclamation, the Department of Energy, and UNESCO. He is author or coauthor of risk maps for the Balkan countries, the United States, and India, and has lectured in seismic hazard assessment in Italy, Indonesia, and Thailand.

ROLAND L. SHARPE is a consulting structural engineer in private practice with more than forty years experience in structural and earthquake engineering. He has been active in development of seismic design code provisions for nearly thirty years. From 1973-1983, he was Executive Director and Managing Director of the Applied Technology Council. While at ATC he was Project Director and Principal Investigator the ATC 3-06 "Tenative Provisions for the Development of Seismic Regulations for Buildings," and for numerous other seismic provision documents.

He served as a member of the board of directors of EERI, SEAONC and SEAOC. As a member of the SEAOC Seismology Committee from 1968-74, he served as Chairman in 1972 and 1973. From 1983-88 he was Chairman of the U.S. Joint Committee on Earthquake Engineering. Currently he is Chairman of Technical Subcommittee #2, Analysis and Design, for the updating of the 1988 NEHRP Provisions. He is author or co-author of nearly 200 engineering papers and reports. He is a registered Civil and Structural Engineer in California.

PAUL C. THENHAUS is a Research Geophysicist with the U.S. Geological Survey. During his 12 years with the USGS, primary investigations have concerned the interfacing of geological data and information with probabilistic ground-motion techniques. He is a member of the USGS Scientific Review Panel to the Nuclear Regulatory Commission rendering reviews on seismic hazards aspects of siting critical facilities and has authored probabilistic ground-motion hazard maps for Western California, Alaska, and Western Saudi Arabia. Recent investigations have concerned the effect of multiple seismotectonic hypotheses on variability of regional ground-motion hazard estimates along the eastern seaboard of the United States and transverse structural zones that segment and terminate north-south belts of young faulting in Utah and Nevada.

CHARLES CONRAD THIEL, JR. is a Consulting Research Engineer providing engineering and scientific consulting services on natural and technological hazards mitigation, civil engineering risk analysis, and systems planning. An area of emphasis is earthquake vulnerability assessment and formulation of hazard mitgation programs. Colaterally, he has an appointment as a Consulting Professor of Structural Engineering at Stanford University and conducts research on earthquake hazards issues, particularly the development of new hazards and risk assessment methodologies using evolving methods of expert systems, fuzzy set theory and artificial intelligence. Dr. Thiel is the founding editor of Earthquake Spectra: The Professional Journal of the Earthquake Engineering Research Institute. Dr. Thiel served as Head of the Federal Earthquake Hazards Reduction Program from its founding and the Chairman of the Interagency Committee for Seismic Safety in Construction until he left the Federal government in 1981. He played a key role in the development and management of the National Earthquake Hazards Reduction Program. Dr. Thiel is a past member of the Boards of Directors of the Earthquake Engineering Research Institute and the Building Seismic Safety Council. He is active in the Seismology Committee of the Structural Engineers Association of Northern California, serving as its representatives on the editorial commentary state committee.

RUSSELL L. WHEELER is currently a geologist in the Branch of Geologic Risk Assessment, U.S. Geological Survey, Golden, Colorado, Dr. Wheeler is a structural geologist by education and training. During his 9+ years with the USGS he has worked mostly in the Appalachians and in Utah, compiling and interpreting what is known of the geologic structure and evaluation of these areas to improve understanding of the faults on which seismicity is occurring or might occur, and to improve estimates of where else similar faults might become active in the near future. This experience led to his current work on revising seismic source zones across the nation.

ROBERT V. WHITMAN is Professor of Civil Engineering at the Massachusetts Institute of Technology. Professor Whitman's original education was in structural engineering, but since then he has been a geotechnical engineer - and indeed much of his work has been in the interface of the two disciplines. To a large extent, his research has consisted of figuring out how to apply the results of other researchers' efforts. He is a past president of EERI, and has served on advisory committees/boards at USGS, NSF, OSTO, FEMA, and the National Academies re-earthquake hazard mitigation. He chaired a committee that prepared the hazard maps in ATC-3, literally drawing the effective peak velocity map himself.

APPENDIX B

CONFERENCES TO DATE

Conference I	Abnormal Animal Behavior Prior to Earthquakes, I Not Open-Filed
Conference II	Experimental Studies of Rock Friction with Application to Earthquake Prediction Not Open-Filed
Conference III	Fault Mechanics and Its Relation to Earthquake Prediction Open-File No. 78-380
Conference IV	Use of Volunteers in the Earthquake Hazards Reduction Program Open-File No. 78-336
Conference V	Communicating Earthquake Hazard Reduction Information Open-File No. 78-933
Conference VI	Methodology for Identifying Seismic Gaps and Soon-to-Break Gaps Open-File No. 78-943
Conference VII	Stress and Strain Measurements Related to Earthquake Prediction Open-File No. 79-370
Conference VIII	Analysis of Actual Fault Zones in Bedrock Open-File No. 79-1239
Conference IX	Magnitude of Deviatoric Stresses in the Earth's Crust and Upper Mantle Open-File No. 80-625
Conference X	Earthquake Hazards Along the Wasatch and Sierra-Nevada Frontal Fault Zones Open-File No. 80-801
Conference XI	Abnormal Animal Behavior Prior to Earthquakes, II Open-File No. 80-453
Conference XII	Earthquake Prediction Information Open-File No. 80-843
Conference XIII	Evaluation of Regional Seismic Hazards and Risk Open-File No. 81-437
Conference XIV	Earthquake Hazards of the Puget Sound Region, Washington Open-File No. 82-19
Conference XV	A Workshop on "Preparing for and Responding to a Damaging Earthquake in the Eastern United States" Open-File No. 82-220
Conference XVI	The Dynamic Characteristics of Faulting Inferred from Recording of Strong Ground Motion Open-File No. 82-591
Conference XVII	Hydraulic Fracturing Stress Measurements Open-File No. 82-1075
Conference XVIII	A Workshop on "Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley Area Open-File No. 83-157
Conference XIX	Active Tectonic and Magmatic Processes Beneath Long Valley Open-File No. 84-939
Conference XX	A Workshop on "The 1886 Charleston, South Carolina, Earthquake and its Implications for Today" Open-File No. 83-843

Conference XXI	A Workshop on"Continuing Actions to Reduce Potential Losses from Future Earthquakes in the Northeastern United States" Open File No. 83-844
Conference XXII	A Workshop on "Site-Specific Effects of Soil and Rock on Ground Motion and the Implications for Earthquake-Resistant Design" Open-File No. 83-845
Conference XXIII	A Workshop on "Continuing Actions to Reduce Potential Losses from Future Earthquakes in Arkansas and Nearby States" Open-File No. 83-846
Conference XXIV	A Workshop on "Geologic Hazards in Puerto Rico" Open-File No. 84-761
Conference XXV	A Workshop on "Earthquake Hazards in the Virgin Islands Region" Open-File No. 84-762
Conference XXVI	A Workshop on "Evaluation of the Regionald and Urban Earthquake Hazards in Utah" Open-File No. 84-763
Conference XXVII	Mechanics of the May 2, 1983 Coalinga Earthquake Open-File No. 85-44
Conference XXVIII	A Workshop on "The Borah Peak, Idaho, Earthquake" Open-File No. 85-290
Conference XXIX	A Workshop on "Continuing Actions to Reduce Potential Losses from Future Earthquakes in New York and Nearby States" Open-File No. 85-386
Conference XXX	A Workshop on "Reducing Potential Losses From Earthquake Hazards in Puerto Rico Open File No. 85-731
Conference XXXI	A Workshop on "Evaluation of Regional and Urban Earthquake Hazards and Risk in Alaska" Open File No. 86-79
Conference XXXII	A Conference on "Future Directions in Evaluating Earthquake Hazards of Southern California" Open-File No. 86-401
Conference XXXIII	A Workshop on "Earthquake Hazards in the Puget Sound, Washington Area" Open-File No. 86-253
Conference XXXIV	A Workshop on "Probabilistic Earthquake-Hazards Assessments," Open-File 86-185
Conference XXXV	A Workshop on "Earth Science Considerations for Earthquake Hazards Reduction in the Central United States," Open-File Report No. 86-425
Conference XXXVI	A Workshop on "Assessment of Geologic Hazards and Risk in Puerto Rico" Open-File 87-007
Conference XXXVII	A Workshop on "Earthquake Hazards Along the Wasatch, Utah Open File 87-154 ,
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Conference XXXIX	Directions in Paleoseismology Open File 87-673
Conference XL	A Workshop on "The U.S. Geological Survey's Role in Hazards Warnings" Open-File Report 87-269
Conference XLI	A Review of the Earthquake Research Applications in the National Earthquake Hazard Reduction Program: 1977-1987 Open-File 88-13-A
Conference XLII	A Workshop on "Evaluation of Earthquake Hazards and Risk in the Puget Sound and Portland Areas" Open-File Report 88-541
Conference XLIII	A Workshop on "Earthquake Risk: Information Needs of the Insurance Industry" Open-File Report 88-669
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Conference XLV	Workshop on "Fault Segmentation and Controls of Rupture Initiation and Terminations" Open-File Report 89-315
Conference XLVI	Seventh US-Japan Seminar on Earthquake Prediction Open File Report 89-[in press]
Conference XLVII	Workshop on "USGS's New Generation of Probabilistic Ground Motion Maps and Their Applications to Building Codes" Open-File Report 89-364

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