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WORKSHOP ON GROUND MOTION PARAMETERS FOR SEISMIC HAZARD MAPPING

July 17-18, 1989

Edited by

Robert V. Whitman

Department of Civil Engineering
Massachusetts Institute of Technology
77 Massachusetts Ave.
Cambridge, MA 02139

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held at
The State University of New York at Buffalo
Buffalo, New York
on
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[1] Professor, Department of Civil Engineering, Massachusetts Institute of Technology

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo
Red Jacket Quadrangle, Buffalo, NY 14261

PREFACE

This document is the product of a Workshop held at the Buffalo headquarters of the National Center for Earthquake Engineering Research. The participants -- listed in Appendix B -- included scientists from the US Geological Survey (USGS) and from the Lamont-Doherty Geological Observatory, and engineers from various parts of the country but primarily from areas of modest or low seismicity. The Workshop followed an earlier meeting on the same general topic, involving the USGS and the Structural Engineers Association of California (SEAOC), held in San Francisco in November 1988 (Hays, 1989). This present report deals primarily with the earthquake problem in areas other than the very seismic regions (California and Alaska), but the conclusions and recommendations may also apply to more seismic regions.

This document is not presented as the final word concerning the choice of ground motion parameters for maps in building codes -- but rather as one step toward agreement upon strategies and implementing measures. The contributors to this report hope that the conclusions and recommendations concerning short term steps can be put to use immediately and that those for the longer term will be discussed and improved at other meetings in the near future, so that soon -- early in the 1990's -- there will be a consensus as to how buildings should be analyzed for design purposes at the start of the 21st century and that the necessary research and implementing studies can get underway.

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SECTION 1
INTRODUCTION

This document is concerned with the choice and definition of ground motion parameters for maps used in model building codes. Such maps specify, for any location, parameters from which earthquake-representing forces are evaluated and used for design and analysis of structures and non-structural components. These maps are also commonly used to establish zones within which certain minimum design requirements -- so-called detailing and ductility provisions -- are imposed. However, utilization of maps for zonation is not the primary concern in this document.

Ground motion maps should change from time to time, reflecting new knowledge concerning the severity and geographical distribution of the earthquake threat, new understandings concerning the relationships between ground motions and structural performance, new capabilities for efficient analysis and design, and increasing acceptance of the importance of seismic design and the role of model codes. Now is such a time. It has been a decade or more since the ground shaking hazard maps used in current model codes were generated. In the interim there has been extensive research in both earthquake seismicity and in structural behavior. The advent of inexpensive computer hardware and software has opened the door to entirely new approaches to the design of earthquake resisting structures. Finally, there is increased interest nation-wide in the earthquake problem.

This document sets forth recommendations concerning the preparation of future ground motion hazard maps, and identifies requirements for the research needed to be able to prepare and utilize these maps. The focus of the report is upon what quantities -- each a simple descriptor of some significant aspect of ground motion -- should be mapped. The recommendations as to the choice of descriptors reflect both the ability of seismologists to map the parameters with confidence and the capability of engineers to utilize them in design. Further, the focus is upon maps to be used in model building codes (and thence hopefully incorporated into legally adopted code requirements). There may, however, be broader uses for the recommendations contained in this report.

Three time scales for the development of new maps are envisioned: *short term* - 2 or 3 years, *intermediate terms* - 4 or 5 years, and *long term* - a decade or so. Changes within the short term must necessarily be modest. While the current knowledge of seismology might permit broader steps, on the engineering and political side there is a natural reluctance to make large changes quickly. For the long term, it is possible and desirable to think more boldly of major changes and advances. One aim of this report is to define what might be desirable and feasible by the turn of the century. Advanced methods of analysis may well be used by many organizations before they become incorporated into model codes, and indeed are used to a limited degree today, while other methods not yet anticipated may be developed.

The next section of this report provides background information concerning the evolution of hazard maps for building codes to their present form. Section 3 discusses the possible future developments in model building codes and the associated needs for ground motion parameter maps. Section 4 discusses current hazard mapping issues. The use of these maps as the starting point for design and analysis is discussed in Section 5. The problem of bringing in the effects of local soil and topographic conditions is the subject of Section 6. The final Section 7 lists research efforts necessary if the recommended maps and analysis procedures are to come into general use by the end of the century.

SECTION 2
BACKGROUND

The first national seismic hazard map, appearing in about 1950, was really a zoning map. Based entirely upon judgment, this map divided the country into four zones assigned to each zone parameters for use in calculating a lateral force coefficient and stated restrictions and requirements upon design in each zone. In the 1970 Uniform Building Code (UBC), this map was superseded by a new zonation map based upon Algermissen's evaluation of the maximum intensity of shaking that had been experienced in each area of the country, although the actual zone boundaries were adjusted based upon the judgment of the drafters of the code.

In 1978 a new form of seismic shaking hazard map appeared in a report prepared by the Applied Technology Council (ATC). This report, generally known as ATC-3, started from a hazard map developed by Algermissen and Perkins[1] based upon the identification of source zones, recurrence rates for earthquakes of different magnitudes in each zone, and attenuation rates for peak ground acceleration. The contours of the Algermissen/Perkins map were smoothed by the committee preparing the ATC-3 recommendations, and in some areas were adjusted to reflect the strong desires of seismologists with local knowledge. The largest peak accelerations, in California, were eliminated, partly by introducing the concept of *effective peak acceleration* and partly by arguing that identification of zones immediately adjacent to faults would constitute microzonation. The map for Effective Peak Velocity was constructed from that for Effective Peak Acceleration, using logical principles but without the benefit of systematic probability-based mapping.

The maps for ground motion parameters appearing in ATC-3, and subsequently used in the National Earthquake Hazard Reduction Program (NEHRP) Provisions (Federal Emergency Management Agency [FEMA], 1988), and -- in modified form -- in the 1989 UBC, were the first probability-based maps in building codes. Still, non-scientific considerations entered into the drawing of the final versions of these maps; e.g. smoothing contours, and -- in the case of the UBC -- changing contour locations in certain states in order to secure the votes of representatives from those states. Taking into account the wishes of local engineers, geologists and building officials poses a difficult question for map makers. Ideally, maps would first be prepared on as scientific a basis as possible, and afterwards adjusted for any political considerations. On the other hand, local engineers and officials may be skeptical that the map makers have really considered local knowledge concerning seismology and geology, and fear that

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[1] Except for Alaska and Hawaii where other information was used.

national maps -- once published -- will have undue influence upon local prerogatives concerning public safety. This Workshop, and others like it, are in part aimed at bridging this potential gap between local engineers/officials and map makers.

SECTION 3

A VISION OF BUILDING CODES IN THE FUTURE

3.1 Introduction

This section describes a strategy for evolution of model building codes in the future, from the standpoint of how ground motion hazard maps will be utilized in the codes. Three time horizons are envisioned:

* Short term - by 1991. Here the strategy is to work within the basic framework of existing model codes, introducing a minimum of change. A specific goal would be to introduce these changes into the main body and appendix of the 1991 revision of the NEHRP Recommended Provisions.

* Intermediate term - by 1994. Now the hope would be to introduce a more rational approach to design using elastic dynamic analysis, but staying with procedures already developed and to some degree in use. A possible goal is to introduce these changes into the commentary of the 1991 Revision of the NEHRP Provisions, for discussion and trial usage leading to inclusion in the main body in 1994. Another possible goal would be incorporation of these changes into the 1994 UBC.

* Long term - say 2000. By this time, it should be possible to introduce methods for dealing explicitly with the behavior of structures in the inelastic range.

The basic new tool for all of these innovations will be an equal probability response spectrum - where the probability of exceedence of spectral ordinates is, for a given annual probability of exceedence, the same for all building periods. In order to make final decisions as to just how this tool will be used, a certain number of maps or information associated with maps must be generated initially to provide a basis for study and trial usage. This need might be met either by:

(1) Generating maps for a reference site condition at annual probabilities of 0.02, 0.01, 0.002, 0.001, 0.0005 and 0.0002, and for building periods of 0.1, 0.2, 0.5, 1.0 and 2.0 and 5.0 seconds[2]; or:

(2) Generating maps for at least two periods and two annual probabilities, plus - at about 20 locations (for a "reference site condition", as defined later) typical of the different seismological environments around the country, generating: (a) plots of spectral ordinates vs. annual probability for each of the periods listed in (1), and (b) equal probability spectra for each of the annual probabilities listed in (1).

In either case, maps for peak ground acceleration and peak ground velocity should be generated at least for annual probabilities of 0.01, 0.002, and probably for 0.01 and 0.0004, for comparison with previously published maps for these two parameters.

One important observation concerning ground motion parameter mapping applies for all time horizons[3]. Motions near faults breaking the ground surface may, during extreme earthquakes, be quite different in character from motions occurring farther from such faults. During such major events, there can be a very large initial pulse of motion involving considerable transient motion. Within such zones - extending possibly to about 15 km either side of a fault - special design requirements may be appropriate for all structures, and it may possibly be inappropriate to extend contours for simple ground motion parameters into such zones.

3.2 The Short Term

The first change to be introduced here is to map two ground motion parameters from which an approximate equal probability response spectrum may be constructed. These two parameters should be a spectral acceleration appropriate for a range of natural periods from about 0.1 to 0.4 seconds, and a spectral velocity appropriate to a range of natural periods from about 0.7 to 2.0 seconds. Rules for constructing a design spectrum and a lateral force coefficient curve from the two parameters will be

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[2] These building periods are tentative, and indicative of the range to be covered. For the Western United States(WUS), it may be more convenient to use 0.3 and 0.7 seconds. For the Eastern United States(EUS), the peak of the equal probability spectrum may lie at a period less than 0.1 second - although such small periods are of little concern for building codes. It is recognized that the accuracy of response spectra ordinates may degenerate at the longer periods, but such periods are important for the design of very tall buildings.

[3] This observation received little or no discussion during the workshop at Buffalo, but was an important item during the earlier meeting in San Francisco(Hays, 1989).

developed in Section 5 and likely will be similar to current practice. To assist in improving such procedures, the engineering community first needs to have equal probability response spectra for a number of typical sites and annual exceedence probabilities for several different periods, as discussed previously.

A lateral force coefficient will be calculated as a function of estimated building period, for those cases where "static" design is appropriate. Since the mapped parameters will be different from those now used in model codes, the numerical coefficients in an equation for lateral force coefficient must be different from those used at present, as discussed in Section 5. The engineering community will need to make this adjustment once the new maps become available.

This design spectrum can be used directly as a basis for design when dynamic analysis is required or permitted by the code following rules set forth in the current versions of the UBC or NEHRP Provisions.

This approach is essentially that proposed in ATC-3 and carried a step further in the appendix to Chapter 1 of the Commentary of the 1988 NEHRP Provisions. In ATC-3, the definitions of the two parameters were vague enough to be unsatisfying, and crude and ad hoc procedures were used to construct the map for the parameter pertinent to longer building periods. The maps in the appendix portion of the 1988 NEHRP Provisions were constructed logically, but are not necessarily well-related to defining equal probability spectra. In a sense, the opportunity and challenge now is to do "correctly" what was proposed and started in ATC-3.

The decision to map only two parameters is a compromise. The selected parameters will perhaps not provide a satisfactory definition for natural periods greater than about 2.0 seconds. On the other hand, it may not be possible at this time to generate reliable spectral ordinates for these longer periods and in the short term a jump from using one map to two maps may be the most that the design professions will accept.

Level of Hazard

A key question is the annual probability of exceedence to be chosen for the maps to be used in the model codes. The Workshop suggested strongly that the annual probability of exceedence should be 0.0005.[4]

This recommended annual probability of exceedence is smaller than that - 0.002 - now generally recognized in model codes as a basis for design. In an area such as California where large earthquakes are relatively frequent, the difference in ground motion parameters for these annual probabilities is thought to be relatively small. Thus a structure designed for the "0.002 'quake" will also very likely survive an "0.0005 'quake". However, in the eastern United States there is a major difference between the strength of earthquakes at these two annual probabilities, and designing for the "0.002 'quake" does not, in the belief of the Workshop, provide adequately for life safety, particularly since detailing requirements are generally lower in the East.

The Workshop discussed how codes could be formulated so that maps for 0.0005 annual exceedence probability might be used to achieve better design in the East without increasing design requirements in areas such as California where practice is now well established. One possible approach would be to use the 0.0005 annual probability maps primarily for zonation, so that the detailing provisions of model codes would be required more extensively in the East, while keeping design lateral forces at the 0.002 probability level. These matters are discussed more fully in Section 5.

It is not at all clear that the profession will be ready for this particular change by 1991. For this reason, maps with an annual exceedence probability of 0.002 should also be prepared.

As described in section 5, it is possible that a dual hazard criteria method for specification of the seismic demand could be incorporated into NEHRP in the short term. Such a method would require maps at two levels of probability. Annual levels of 0.02 and 0.0005 are suggested.

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[4] An annual probability of exceedence of 0.002 corresponds to a mean recurrence interval of 500 years or approximately to a 10% probability of exceedence in 50 years, which is the basis of current maps. For an annual probability of 0.0005, the corresponding alternative expressions are 2000 years or 2% in 50 years; an annual probability of 0.01 corresponds to 100 years or 60% probability of exceedence in 50 years.

Duration

The consequences of duration are not specifically accounted for in this procedure, because no procedure for doing so has yet been developed to the point of acceptance. The engineering profession would welcome the opportunity to examine measures of duration for future utility, but such measures could not be incorporated into codes in the near term.

3.3 The Intermediate Term

At this stage, it is possible that two-level design might be introduced as an alternative to the one-level approach to design now in use and a logical refinement of the dual hazard criterion suggested for the short term.

In two-level design, a building is first designed to remain elastic during a ground motion that is reasonably expected to occur during the life of the structure, and then - after detailing as required by the code - is checked to ensure that collapse will not occur during a more intense motion. In effect two limit states are considered - continued functioning and survivability. For the intermediate term, both checks would be done using elastic response spectra as input, following procedures such as those currently set forth in the Tri-Services Manual (U.S. Army, 1986). The analysis for the more severe earthquake may be performed assuming elasticity, or at least incremental inelasticity, and is used to evaluate the ductility demand upon the structure. Two equal probability spectra would be needed for two-level design, tentatively one for an annual exceedence probability of 0.02 or 0.01 and a second for an annual probability between 0.001 to 0.0002. Variations in probability could well be used to account for the importance of certain facilities as well as for evaluation of existing buildings.

The engineers at the Workshop recommend moving to two-level design. Recognizing that many other engineers in the country may still be skeptical of this approach, just how it might work must be examined further. Two-level design does <u>not</u> necessarily mean that "the design earthquake is being 'jacked up'", but rather is a more systematic method for achieving the same objectives as one-level design, and generally the result will be structures that are both safer and more economical. The set of maps or hazard curves discussed previously are needed as a basis for examining the issues involved in implementing this approach.

One-level design would remain as an acceptable procedure for many types of structures. Two-level design would be required for certain types/sizes/shapes/locations of buildings, and would be an option for all structures.

Duration

As described above, no account would be taken of duration. Possibly by the intermediate term approximate methods for accounting for the effects of duration may be developed. Several suggestions have been made for so doing: using the 3rd or 5th highest spectral response rather than the peak response, or weighing spectral ordinates according to the magnitude of the causative earthquake. Such possibilities should be pursued.

However, it can be stated clearly that structural engineers at this Workshop were not interested in having a map of duration. Rather, the important issue of duration must be considered as part of entirely new mapping strategies related to structural response.

3.4 The Long Term

It is anticipated that the lower level of the two-level design will still be carried out using response spectrum techniques, using for input the same spectrum described for the medium term. However, improved methods will be employed to check the design against collapse during the higher level earthquake. Several such procedures have been suggested:

- Non-linear response spectra might be used to account for the energy dissipated. This approach would require mapping of non-linear spectral ordinates for simple structures.

- Time history analysis might be used to evaluate the expected inelastic excursions. This approach would require behavioral models for various types of structures in the inelastic range, and would require mapping of parameters from which suitable accelerograms (artificial, or scaled actual recordings) could be selected.

These and other procedures would explicitly account for the effect of duration of shaking upon the safety of a building. All such possible methods, and their implications for mapping, should be pursued to the point where the most promising approach can be identified. In particular, seismologists should begin to consider how to "map" appropriate accelograms for various parts of the country.

There would still be a one-level design alternative for the long term, applicable to certain classes of buildings. Hence, maps of ground motion parameters required for such methods will still be necessary. By this stage, the profession should have learned how to bring the effect of duration into one-level analysis in a meaningful if approximate manner, and should by then be able to accept more than two maps for the necessary parameters.

3.5 Site Effects

Any one ground motion parameter map can apply only for one specific site condition, reflecting a certain soil profile and topography. In concept one might imagine different maps for different site conditions. However, because of the enormity of possible site conditions, this approach is not feasible on a national level - although local or regional mapping is both possible and desirable. Hence, national maps must be associated with one or two well-defined reference site conditions, together with provisions for evaluating the effect of local conditions.

Reference Site Conditions

As discussed in Section 6, the task of defining a reference site is not simple - in part because of inadequate data for ground motions at different types of sites and in part because the seemingly obvious choice for a reference site - "rock" - varies in nature and typical depth of occurence across the country.

As a starting point, the Workshop recommends that initial maps (or equal probability spectra and hazard curves for a number of locations) be prepared for two types of reference site conditions: "hard rock" (which might be defined as having a shear wave velocity of at least 3200 m/s) and "stiff deep alluvium" (essentially an S2 site in the current model codes). Since actual strong motion data in the Northeast were collected on hardrock while those in California were recorded primarily on stiff deep alluvium, for each part of the country a conversion between the two types of sites must be developed. Methods for use in model codes, to convert to other site conditions must be developed for general use[5]. In particular, the conversion from hard rock to "soft rock" (shear wave velocity > 700 m/s) as commonly utilized in California, should be established. All data that might allow comparisons between motions on "hard" vs. "soft" rock should be examined in detail.

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[5] At the Workshop there was considerable skepticism concerning theoretical analyses involving a soil/rock column thicker than about 100 m. There is no objection to the use of theoretical methods in helping to develop suitable methods for dealing with deep profiles.

This problem needs more attention than it has been possible to give to it at this Workshop. Another workshop, specifically devoted to this question and preceded by studies and analyses to indicate the feasibility and practicality of various possible approaches, is urgently needed.

Evaluating Local Site Effects

When lateral force coefficients are used for design, soil factors will continue to be used and in the long term topographic factors may also be used. For the intermediate and long term, it may well be necessary to develop more than the four "standard soil profiles" now appearing in codes. It has also been suggested that a larger soil factor may be needed for a given soil profile in the East as compared to California, because of the typically larger impedance contrast between soil and rock in the East. It is anticipated that the use of dynamic site analysis will increase in the future, and user-friendly software and guidelines for performing satisfactory analyses should be developed(but see footnote 5).

Liquefaction and Ground Failure

Ground motion maps do not deal with these important concerns, although the level of ground motions is important for deciding whether or not such events might occur. Model building codes generally do not address these problems at all (but liquefaction is addressed in the Massachusetts State Building Code), and it would be desirable for future model codes to contain some guidance concerning such matters.

SECTION 4

SEISMOLOGY AND MAPPING

4.1 Introduction

Hazard maps require data about complex earthquake phenomena and a formulation that translates this knowledge into a few mappable parameters. While computational methods are well developed, understanding of the earthquake generation process is still evolving and is a primary source of uncertainties in the evaluation of hazard. Short-term concerns will focus on strategies to exploit available data to the fullest while long-term consideration should focus on the data base and on a better physical understanding of earthquake processes.

4.2 Computational Methods

Most seismic hazard analysis methods are based on the Cornell-McGuire approach(Cornell, 1968; McGuire, 1976; 1977), in which judgements concerning the earthquake-causing geological structures and processes are incorporated through the definition of seismic source zones, Three approaches to the definition of source zones have been identified, each of which handles the subjective aspects in a somewhat different manner.

The traditional approach has been to combine judgements on the distribution of earthquake activity with judgements regarding active and potentially active geologic sources, to produce a single best-estimate set of seismic source zones (Algermissen et al., 1982; Basham et al., 1982).

While such an approach has been used extensively in the past, it has been difficult to combine geology and seismicity in a clear, defendable manner. This approach tends to reflect, in part, currently popular hypotheses of geologic causes of seismicity. However, these hypotheses rise and fall given new data or reinterpretations of old data, and hence it is not always clear whether a change in existing source zones is a true advance or an error.

A second approach, pioneered by the Electric Power Research Institute (McGuire & Toro, 1986), attempts to render explicit the judgments that go into identifying an earthquake source and its seismic potential. Through the use of matrices and logic trees, these procedures require explicit subjective probabilities that combinations of chosen physical attributes can cause earthquakes and that particular features are characterized by those physical attributes. Such procedures allow for free expression of hypothetical earthquake sources and causes while allowing the identification of subjective input through explicit, subjective probabilities. However, in application to the EUS where no clear consensus exists on such sources and causes, the tendency is to base the weighing on the spatial association of seismicity with identified geologic features.

A third strategy, not yet fully implemented but proposed by the USGS for code development purposes in the East (Algermissen, 1989), is fashioned as a best-estimate approach that separates the geological and seismological considerations in developing the hazard estimates. Regional geologic structure and geologic history are used to define a few (less than 10) large geologic source zones in the East. These geologic sources differ in the documented ages, types, abundances, orientations, sizes and likely mechanical properties of their faults at seismogenic depths. The underlying assumption is that such geologic attributes govern very long-term, mostly low-likelihood hazard (hazard averaged over a period much longer than the historical record of earthquakes). Within the regional geologic sources, historical seismicity is used to identify more local areas of comparatively high hazard (shorter-term hazard averaged over hundreds of years as the historical records of earthquakes suggests). Such a treatment recognizes the persistence of the spatial distribution of Eastern seismicity, but also implies that seismicity concentrations turn on and off in a geologic source zone, or migrate, or become contagious within a zone over a period of time much longer than the historical record of earthquakes in the Eastern U.S. Subjectivity is documented and quantified in terms of smoothing estimates of parameter values based on the historical seismicity concentrations and making uncertainty estimates on the spatial locations of the boundaries of geologic source zones. Consequences of modeling alternative hypotheses regarding earthquake sources would be shown in separate ground motion maps for comparison to the recommended map.

The choice of a method for code-development purposes should be based on the following considerations:

1. Stability. Incorporation of seismic design requirements into codes takes a long time -- on the order of ten or more years if history indicates future trends. Therefore, a hazard mapping strategy should be designed as fundamentally as possible, avoiding conjecture but reflecting the current state of knowledge.

2. Transparency of approach. Significant complexity engenders distrust. Because adoption of design requirements in local codes follows a largely political course, it is

useful to maintain as little complexity as possible, in order to be as widely understood as possible within the engineering and building community.

3. Traceable results. Final ground-motion estimates should be traceable through the computational strategy, so that mapped ground motions can be readily interpreted in terms of inputs (e.g. ground-motion attenuation properties) and computational procedures.

4. Regional perspectives. National hazard maps must incorporate regional perspectives to ensure compatibility with local code requirements.

4.3 Source Zones and Recurrence Relations

In the Central and Eastern United States there are few established active faults, and most source zones should be considered as areas. Small individual structures should not at present be used as source zones because the geological and seismological evidence for the uniqueness of such small zones is not convincing.

Methods of defining source zones, as discussed above, differ in their basic assumptions and treatment of subjective input. In general, however, the source zones attempt to identify areas with a uniform probability of future earthquake occurrences, based on some combination of seismicity and geologic data.

The probability of earthquake occurrences within each zone is then described by a recurrence relation. The Gutenberg-Richter relation (Richter, 1958), or similar, has been most commonly assumed, although other models (e.g., time-predictable or slip-predictable) have been gaining increasing acceptance for describing observed fault behavior. Cornell and Winterstein (1988) have investigated the implications of a broad set of recurrence models with temporal and magnitude dependence, and identified the conditions under which the Poisson model provides a sufficient engineering hazard estimate. In practice, the Poisson model is insufficient only if the hazard is controlled by a single feature for which the elapse time since the last significant event exceeds the average time between such events. Present geologic methods do not generally enable us to identify such features in the eastern U.S.

There thus appears to be insufficient information or justification to apply any but the simplest of earthquake models to the Central or Eastern United States. It is anticipated that the traditional Poisson model of occurrence will be maintained, with recurrence relations specified by the Gutenberg-Richter relation.

4.4 Ground Motion Relations (Attenuation)

Ground motion relations, specifying the source levels and attenuation with distance of the mapped ground motion parameters, are ideally developed by regression analysis of a large strong motion data set, for the desired site conditions. For mapping purposes rock relations would be most convenient since this represents the 'base' site condition. In California, there is a good empirical database, although most data are for soil alluvial sites. Therefore, western ground motion relations are based on regression of actual data (e.g., Campbell, 1981; Joyner & Boore, 1981; Joyner & Boore, 1982). For Eastern North America (ENA), the data set consists of approximately 100 rock records for M4½ to 7 events (but mostly 4½ to 5½) at distances of 10 to several hundred km. The data are insufficient for reliable regressions over the entire magnitude range. However, there is an emerging consensus that theoretical models can help to fill the gaps in the database, by providing a physical basis for the magnitude-scaling of motions (Atkinson, 1984; Boore and Atkinson, 1987; Toro and McGuire, 1987; Mc Guire et al., 1988; Atkinson and Boore, 1989 a). The combined use of models and data enable median ground motion relations for eastern rock sites (shear wave velocity ≈ 3.5 km/s) to be specified with reasonable confidence. An alternate approach to ENA relations is to utilize California ground motion relations, making appropriate corrections for differences in near-surface geology and wave propagation (Campbell, 1989).

There is some concern that current ENA models may not be a good representation of ground motion for recent significant events. Such models (e.g., Atkinson & Boore, 1989a) seriously underestimate high-frequency motions observed during the Saguenay, 1988 events (although low-frequencies are overestimated)(Atkinson & Boore, 1989b); on the other hand, the models overpredict the observed Nahanni ground motions (Boore & Atkinson, 1989). There may be much inter-event variability at high frequencies.

For consistency it would be desirable from the seismological viewpoint to use ground motion relations for hard rock sites for all parts of the U.S. However, for the WUS, only a small portion of the existing strong-motion data base has been recorded on hard rock, so attenuation relationships are not as reliable for hard rock or as readily available as those for alluvium. Therefore, it may be better to use soft rock or alluvium as a reference site in the WUS, then adjust estimates of ground motion for other site conditions and map the appropriately adjusted ground motion parameter. In principal, attenuation functions derived in this manner for the west could be empirically converted to the same "base rock velocity" as the east, thus standardizing the national map to one base. This approach also has the advantage that subsequent corrections for site effects would be simplified and could include nonlinear soil behavior at specific sites as needed.

4.5 Treatment of Uncertainty

The treatment of uncertainty in seismic hazard analyses is a critical issue, because ground motion results can vary by factors of 2 (typically) to 10 (in cases where limited knowledge permits extremely different basic hypotheses (Atkinson et al, 1987). Two basic types of uncertainty are recognized (McGuire & Toro, 1986): (i) that due to physical variability (e.g., the scatter of ground motion values about a regression line); and (ii) that due to imperfect knowledge concerning seismic hazard (e.g., different results obtained from different source zone definitions). The first type of uncertainty is physical-based and cannot be eliminated (although it may in some cases be reduced by use of more sophisticated models). The second type of uncertainty should decrease with time as our knowledge improves.

The physical variability of ground motion, typically characterized by some σ value for the ground motion relations, must be included in the hazard analysis in order to obtain the expected ground motion values for the desired probabilities.

The treatment of uncertainty due to lack of knowledge is more problematic. Typically, results for ENA are most sensitive to uncertainties in the definition of source zones, and uncertainties in the median levels for the ground motion relations. One approach to incorporating these uncertainties is through the development and subjective weighting of alternative hypotheses for the key parameters (e.g., such as the EPRI approach). Another approach is to rely largely on developing 'best estimates'. For the short-term, the latter approach is most likely to be adopted by the USGS for zoning maps in order to make factors contributing to the results more apparent (Algermissen, 1989).

The consideration of tectonic uncertainty warrants further discussions. Any site in the East is underlain by faults of several types and ages. Drawing a source zone may require identifying the type and age of fault that causes earthquakes in the zone, and mapping the area in which similar faults exist. This area is the source zone. Uncertainty in such source zones comprises (1) interpretational uncertainty of geological models, (2) locational uncertainty of seismicity, (3) uncertainty about the stationarity of seismicity, and (4) uncertainty about how one combines geology with seismicity to draw source zones.

Items (1) - (3) can be treated by describing the sizes of the uncertainties. There are three main approaches to (4), as described previously in Section 4.2.

In most hazard analysis computer programs, areal sources are required to have well-defined boundaries, and modeled earthquake rates, *b*-values[6] 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. It may be appropriate to model seismicity as changing gradually rather than abruptly at source boundaries (fuzzy boundaries).

4.6 Other Matters

The choice of minimum magnitude can have a significant effect on calculated proabilistic peak accelerations and equal hazard response spectra at lower ground motion values (Bender & Campbell, 1989). To reflect our current uncertainty in the damageability of small magnitude earthquakes, a tapered, rather than abrupt, minimum magnitude cutoff should be considered.

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[6] The b value gives the slope of the Gutenberg-Richter relation between magnitude and frequency of occurrence.

SECTION 5

REQUIREMENTS FOR ANALYSIS IN DESIGN

5.1 An Assessment of the State of the Art

Design of the structural system for a building, bridge or other structure is properly a trial-and-error process. An initial design is created. Then an analysis is made, using member stiffnesses corresponding to the initial design, to evaluate the forces and bending moments in members as a result of specified loading conditions. If necessary, the designs for one or more members are then adjusted. For some simple structures, the initial design may not be checked by further analysis; experience has shown that use of approximate procedures for estimating forces and moments leads to a satisfactory design.

For the initial design, some estimate must be made of forces and moments in all members. This is done using a simple procedure that anticipates the final stiffness of the various members and of the structure as a whole. Simple rules for estimating earthquake-induced forces are essential at this stage. In other words, lateral force coefficients are necessary for initial design even if dynamic analysis is subsequently used to give better evaluations of member forces/moments as a basis for adjusting and finalizing the design.

Code provisions covering design of structures against earthquakes are, today, aimed at life safety. A structure properly designed to these code provisions may well be damaged if an extremely severe earthquake occurs during its lifetime; indeed, it is assumed that many structures designed to the code will experience some damage during any such earthquake. Design involves: (a) proportioning members for induced forces/moments less than those anticipated were the structure to remain elastic, during the extremely severe earthquake and (b) using detailing to give the structure the "toughness" or "ductility" needed to hang together and thus continue to support dead and live loads during repeated straining beyond the yield point. The latter characteristic of a structural system is expressed in codes by the R factor. Current codes use a single value for all frequencies to make this adjustment from elastic response level to inelastic design level. Achieving the balance between design for reduced forces and ductility is the essence of good earthquake engineering. While these two aspects of engineering cannot totally be separated, this Workshop has focused upon loadings and forces and has not considered further the requirements for proper detailing nor the characterization of different structural systems with regard to R factors.

Evaluation of seismic life safety of existing buildings is a rapidly developing area. The analytical procedures for design of new structures are used essentially unmodified in the evaluation of existing structures, although levels of safety are usually somewhat different. Future advances in characterization of seismic ground motion will also help advancement of this field.

As regards the specification of ground motions for design or evaluation, a major challenge is to relate the characteristics of ground motions to the behavior of structures when these structures are stressed into the inelastic range, taking into account the possible degradation of stiffness and strength as a result of repeated inelastic excursions. The number of such excursions, and hence the duration of the ground shaking, is of particular concern. A number of approaches to this problem have been suggested:

- Various researchers have developed techniques for constructing inelastic response spectra. Such spectra, when used for design, are intended to ensure that actual inelastic straining -- i.e. ductility demand -- is no greater than the inelastic straining -- expressed as a ductility ratio -- assumed in developing the spectra. Ordinates of the spectra have been related to specific characteristics of ground motions, such as peak ground acceleration and peak ground velocity. Work by *Turkstra & Tallin* (1988) indicates how such spectra might be determined directly from the magnitude and distance from an earthquake. Taking into account duration has been of special concern. Studies by *Sewell* (1988) suggest that perhaps duration is not really an issue; that is, that the appropriate reduction from elastic spectra may be independent of magnitude and distance, and thus implicitly independent of duration.

- *Bertero* (see Hays, 1989) has suggested that emphasis should be placed upon the energy that a structural system must be able to absorb without excessive damage, and that we should be mapping ground motion parameters related to this energy demand. A structure once designed would be checked for its ability to absorb the required energy, perhaps by assessing the absorption capacity of all connections. This approach would avoid the necessity of dynamic analysis within the inelastic range. As yet, however, just how this approach would work has not been spelled out in detail.

- Use of time series analysis within the inelastic range. In one sense this would be the best method for ensuring that the degree of straining remains within the range where the structure can continue to stand and protect life safety. On the other hand, however, methods for characterizing the non-linear behavior of structural members and structural systems still are not well accepted, and the computer software necessary for performing the analyses is not generally available or affordable. Rapid development and dissemination of satisfactory software is anticipated, however.

These approaches all appear to be in the long-term area. In the short term, the "frequency blind" single factor adjustment will continue to be used.

Equations or curves for lateral force coefficients are based upon a number of considerations. In the past they have included adjustments from the theoretically pure response spectra. Ordinates at larger periods are usually increased to account in an approximate way for the contributions of higher modes and uncertainties about the robustness of large structural systems. A structure's fundamental period is affected by how strongly the structure is shaken, and in any case may not be known with great accuracy. At very small periods, ordinates are increased, partly in recognition that as a very stiff structure is damaged its period increases into a range where dynamic response is increased, and partly for the sake of simplicity. Finally, values for lateral force coefficients have been based in large part upon the behavior of structures during actual earthquakes. Hence the relationship between an elastic response spectrum and a curve of lateral force coefficient is rather complicated and has in the past been based upon considerable judgment. It is likely that similar adjustments will be included in future lateral force coefficients. However, mapping equal probability response ordinates is desirable. The adjustments should be made after mapping, not before.

In the 1988 NEHRP Provisions, the lateral force coefficient at small periods is linked to a parameter called effective peak acceleration, while the parameter controlling the coefficient at long periods is denoted as effective peak velocity. These two parameters were in turn related to average (in relation to period) ordinates of response spectra, although the connection was approximate at best. In the appendix to Chapter 1 of the Commentary of the NEHRP Provisions, where it is suggested that peak ground acceleration and peak ground velocity be used as mapping parameters, there is a discussion as to how these new parameters should be used to give lateral force coefficients correlated to those calculated (in the actual provisions) from effective acceleration and velocity.

The 1988 UBC, following the past practice for that model code, simply maps a zone factor -- which is, however, more-or-less related to the effective peak velocity of the NEHRP Provisions.

When the mapped parameters become response spectral related ordinates, as recommended in Section 3, it will be necessary to develop new relations between these parameters and lateral force coefficients.

For the short term, the form of the equations for base shear and lateral force coefficient should be that in the 1988 NEHRP Provisions:

$$V = C_s W;\ C_s = X_2 S_v S/RT^{2/3} \text{ or } C_s = X_1 S_a/R, \text{ whichever is smaller}$$

where S_a and S_v are response spectral ordinates and X_1 and X_2 are numerical coefficients with values to be determined. Other symbols have conventional meanings. In the long term, the equation for base shear and lateral force coefficients may well be similar, due to the need for simple methods for initial design.

It appears possible to produce and desirable to have maps that present more ordinates to better define a response spectrum. Specific rules must be established for creating smooth design spectra from the mapped spectral ordinates. These rules may or may not be the same for the short and long term.

In the current codes, modal analysis using response spectra input is used primarily to provide a more satisfactory evaluation of how the base shear is actually distributed through the stories and members of a structure. The actual level of the forces and moments are adjusted so that the corresponding base shear is more-or-less consistent with that calculated using lateral force coefficients. In the 1988 UBC, a slight decrease in calculated base shear is permitted if modal response techniques are used. In the NEHRP Provisions, the provision is similar.

Two-level design procedures have been introduced for some classes of structures. The initial step is to check the initial design for performance during the earthquake reasonably expected during the life time of the structure -- with the structure not to yield for this loading condition.

The second step is to check stability against collapse given an earthquake with a much lower probability of occurrence. Starting with a design check for the "reasonably expected earthquake" may seem inconsistent with the idea that codes are protecting life safety and not necessarily protecting against damage. However, yielding of the structural system is the point at which life-threatening damage to secondary systems (plumbing, overhead fixtures, etc.) and interior/exterior walls can begin. The procedures followed in performing the analyses are essentially those in use today. One aspect of the design procedures that may need to be re-examined is the load factor to be placed on the earthquake-induced stresses.

Further development of these two-level design approaches is expected, with consequent need for maps at multiple levels of probability of exceedance. A simple extension of this philosophy appears likely to be developed for ordinary buildings in which only one structural analysis is performed but two levels of seismic ground shaking are checked in developing the controlling one for actual analysis and design.

The following sections present specific predictions and needs for the short, intermediate, and long terms. The most important recommendations can be capsulized as:

- Seismic hazard maps should present scientific information for equal probability response spectra unmodified by engineering adjustments.

- More and different levels of probability are needed, coupled with a likely move to a lower probability of exceedence for life safety issues and to dual hazard criteria and two-level design approaches.

- More rigorous accounting for inelastic action is at least an intermediate term and probably a long term issue.

5.2 The Short Term

Both the UBC and the NEHRP Recommended Provisions are scheduled for revisions in 1991 and 1994. Committee work towards these revisions has already begun. Given the large change introduced in the 1988 UBC, the short-term changes will probably be minor and evolutionary. One of the most likely areas for change, given the widespread dissatisfaction with the UBC mapping process in 1988, is the seismic hazard maps. The maps are used both to set levels of strength required and to define zones where special detailing rules are required. New maps should affect both uses. To be useful for the 1991 updates, draft versions of new maps would be necessary by 1990. It is likely that the full scope of potential short term changes in mapping will not be incorporated into the UBC and NEHRP until the 1994 editions.

The nature of the seismic ground shaking hazard varies a great deal across the nation. Of concern to structural engineers is that the differing shape of the hazard curve for given response parameter at different locations results in potential inequalities in safety when a single level of probability is used. (A hazard curve is herein defined to relate the magnitude of a particular parameter to the level of probability for a single location.)

Figure 5-1 reproduces in schematic form, several preliminary hazard curves for several cities prepared by the USGS for this Workshop. The parameter on the vertical scale is the peak ground acceleration that has a 90% probability of not being exceeded in the exposure time on the horizontal axis. Current codes are based on this 90% probability of not exceeding the given map values when considering a 50-year exposure time period. Examination of the various curves of the figure reveals the following: The acceleration in relatively high hazard areas such as Anchorage and the cities of California at the 50-year exposure time period is a large percentage of the values associated with the 250 year exposure. In contrast, the New Madrid and Wasatch Front areas have acceleration values at the 50 year exposure period that are roughly 1/2 of the values at the 250 year period. Many other areas of the EUS have similar seismic characteristics as these latter two areas. That is, they have infrequent large earthquakes.

The ratio of the possible force to the actual design level is of concern in the engineering community. It appears that the ratio of the forces that would be generated by a rare, but possible, earthquake (i.e., an event that could be expected to occur in the 200 or 250 year exposure period) to the basic design forces of current codes is significantly larger in the EUS (and other areas such as New Madrid and the Wasatch Front) than the California areas, where most of the real-life experience with performance in earthquakes is centered. It appears likely that the longer term event should become a basis for design codes. This is particularly true for the "lower" zones where buildings are not built with the benefit of ductile detailing.

It is recommended that seismic ground motion maps be produced that are based on the concept of equal probability of collapse or extreme damage to the associated structures. These maps, focused on the life safety aspects of building design, should reflect an annual probability of exceedence of between 0.001 and 0.0002. They would be used to scale various response spectra curves as well as dividing areas into seismic zones. It is not anticipated that they would be used directly without modification for establishing design force levels.

It is noteworthy that the Zonation Subcommittee of the Seismology Committee of the Structural Engineering Association of Northern California recommended in 1982 that the 2,000-year earthquake be used in developing zonation maps (Matthiesen, et al. 1982). The choice of 2,000 years was selected because the committee believed it reflected a probability or risk comparable to other risks that the public accepts in regard to life safety. The sub-committee also observed that the mean recurrence intervals for maximum earthquakes on long faults with low slip rates may be substantially longer than

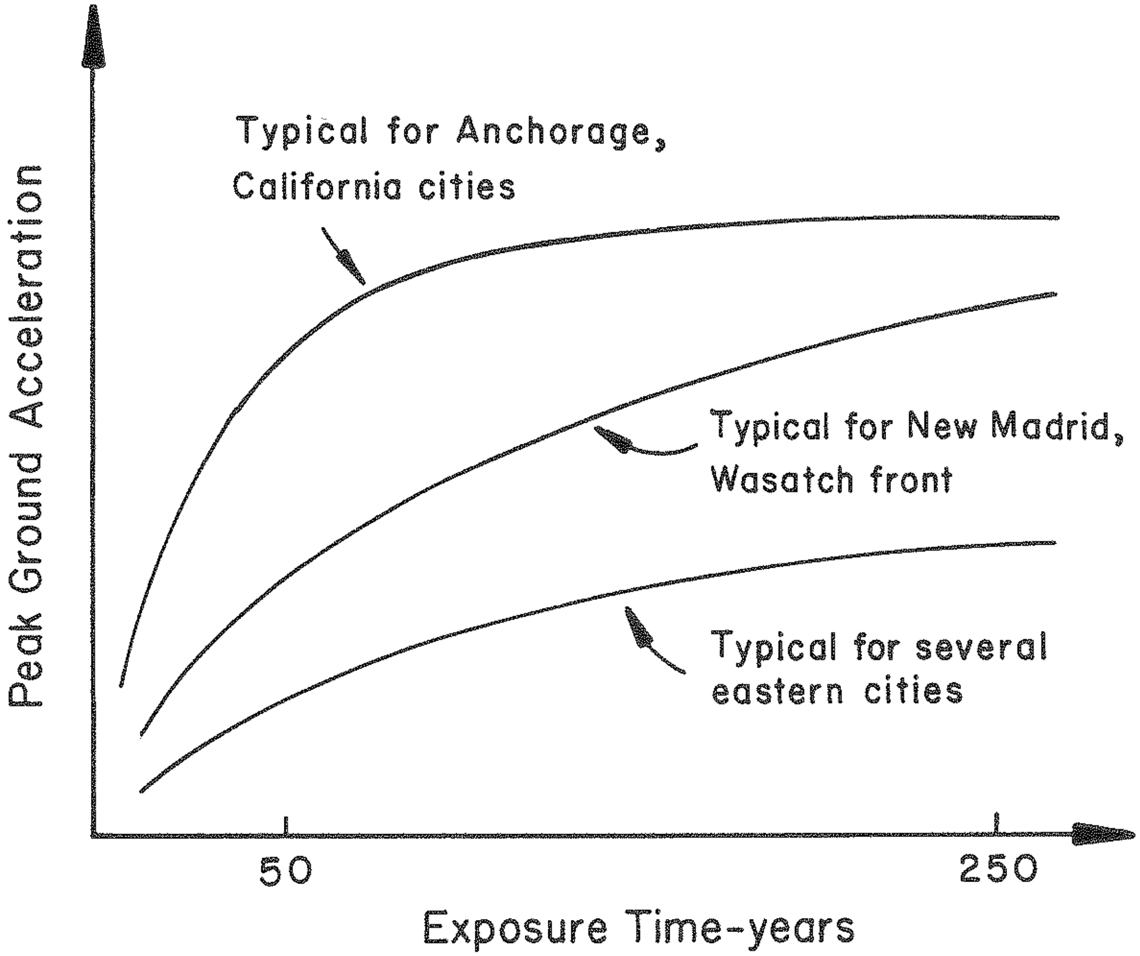

FIGURE 5-1 Schematic Hazard Curves for Several U.S. Cities

2,000 years, but that the use of longer return periods would be generally considered an unreasonable basis for code requirements.

There are other trends that impact the level of probability used for expression of the seismic hazard. In high hazard areas increasing attention is being paid to economic performance, specifically that damage be limited in the event of a "probable" earthquake. In lower hazard areas there is a desire to correlate the standards for earthquake resistance with those for other loads. There is also increasing concern about how to provide higher reliability for essential facilities. All of these issues essentially are requesting further information on the seismic hazard at various levels of probability. At this time it appears desirable to have statements of the seismic hazard (maps) at the following probabilities of yearly exceedence; the associated possible uses are also indicated:

0.02	Elastic strength for ordinary buildings
0.01	Elastic strength for essential facilities
0.002	Current standards
0.001	Collapse strength for ordinary buildings (?)
0.0005	Collapse strength for ordinary buildings (?)
0.0002	Collapse strength for essential facilities (?)

Obviously the engineering community will face decisions about the specific use of precise probability levels. The decision-making process will be facilitated by production of these maps for evaluation.

Spectral Response Ordinates

Current design procedures are based on maps of peak ground acceleration and velocity. It is well recognized that these are not appropriate values for direct use in structural design, and hence they are modified based on both scientific information and engineering judgement. These adjusted values of acceleration and velocity are used to define a design response spectra.

Data are now available so that response spectral ordinates can be mapped at different periods. This approach allows direct definition of the design spectra. In order to maintain a definition of spectra obtained by the use of such maps equivalent with that used in current practice, two ordinates are required -- one in the velocity region and one in the acceleration region.

It is recognized that the spectral shape may or may not be adequately defined by only two ordinates. The shape may vary by region and/or probability level. The spectral ordinates should be evaluated periods such as 0.1, 0.2, 0.5, 1, 2, and 5 seconds, so that sensitivity of shape to location and probability level can be studied. This effort should be carried out at probability levels previously indicated. This would allow determination of the minimum number of ordinates necessary.

Should two ordinates be satisfactory, there are preliminary indications that spectral ordinates determined at periods T = 0.1 to 0.2 seconds and T - 1.5 to 2.0 seconds may be adequate to define the response spectra. To use these spectral ordinates in the format of current codes, it will be necessary to develop new relations between these parameters and lateral force coefficients, as discussed previously.

The preparation of maps is not trivial. Also, 36 nationwide maps (six levels of probability and six ordinates of a response spectrum) would be awkward to use. Consequently, the shape of the spectra and the hazard curves should be studied at selected locations, on the order of 20 to 25. Studies of these results likely will show that it suffices to produce initially a smaller set of nationwide maps.

For use in 1991, maps of two parameters at three probabilities levels, 0.02, 0.002, and 0.0005, appear to present all the information necessary for pursuit of two viable options. The additional maps would be useful for 1994 updates (committee work in 1992 and 1993).

One viable option for implementation of these results is that NEHRP directly incorporate the maps based upon an annual probability of 0.0005. The map will be used to delineate zones of approximately equal seismic design requirements. The design force would be taken from the maps using essentially the same procedures currently used; however the force would be reduced somewhat to account for the strength of structures that is not represented in typical analysis procedures and for damping and inelastic response effects. In this way the values will be in general reduced to appropriate levels for design.

A second viable option is that the design force level could be established from a dual criterion: one criterion would derive a seismic coefficient from maps at the 0.02 or 0.01 level of probability and the second from the maps at the 0.0005 level. The first criterion would not be modified from the elastic response while the second one would be modified. This would allow engineers the flexibility to provide the capacity for the low probability event by balancing strength and detailing requirements. For example, detailing for a higher "R" factor would allow reduction of the elastic strength required.

In summary, the short term needs are:

1) By 1990, maps showing two ordinates for response spectra at three levels of probability: 0.02, 0.002, and 0.0005.

2) Also by 1990, fuller definitions of response spectra and hazard curves at 20 to 25 locations.

3) By 1992, maps at the ordinates and probability levels selected.

5.3 The Intermediate Term

Dual-Criteria, Two-Level Design

The design and analysis of a building using current seismic risk maps and the equivalent static lateral force method may prove to be seismically inadequate if a major earthquake results in demands several times the design capacity. This is of particular concern in the EUS where a lower probability but major earthquake could induce maximum ground accelerations greatly in excess of the current building code design levels and by margins considerably greater than would occur in the high risk western regions.

It is anticipated that future building code design methodology will require two distinct levels of design earthquakes. They are the performance-level and the life-safety-level earthquakes. Through the design process, these dual design criteria would insure that building construction represents functional adequacy and economy while reducing the potential for catastrophic failure of earthquake-resistant buildings should a major earthquake occur. Following the suggestion of U.S. Army Technical Manual TM 5-809-10-1, Seismic Design Guidelines for Essential Facilities, the design process would consider dual criteria applied in two phases. The first phase would design the building to an acceptable level of performance response to a lower level, moderate earthquake (e.g. a 50 year event termed EQ-1). Performance would be judged from the stresses as determined by elastic analysis. As such, it would ensure sufficient capacity to meet life safety demands at this lower level earthquake. The second phase would analyze and design the building to ensure life safety in the event of a higher-level earthquake, a "maximum credible earthquake" taken as that with a 2,000 year mean recurrence interval. Analysis would be by elastic linear methods, but the design would account for inelastic behavior, ductility demands, potential instability and damage control as described in the Technical Manual.

In this design approach, the design response spectrum is developed according to the NEHRP provisions. With the peak ground accelerations known for the two design earthquakes, only the structural damping and site soil profiles (S_1, S_2, S_3, S_4) would need to be established before the response spectra could be developed. The inelastic response of the second phase, or life-safety design level, would be incorporated through the use of increased damping multiplier factors applied to the lateral force coefficient.

In regards to the life-safety level, the analysis procedure assumes that a number of lateral-force-resisting elements would be stressed beyond their elastic limit yield capacities. The calculated forces on the structural elements would be determined using an elastic analysis as discussed above. These are the force demands of the life-safety level analysis were the structure to remain elastic. The capacity is the strength of the element at the point of yielding. The ratio of the demand to the capacity (i.e. the inelastic demand ratio) is an indication of the ductility that may be required for the structural element to withstand the forces of the life-safety level. The limiting values of inelastic demand ratios for structural elements are as provided by TM 5-809-10-1.

Possible weak links in the overall structure are identified by investigating the distribution of the inelastic demand ratios that exceed a value of 1.0. Appropriate adjustments are then made.

The dual-criteria, two-level design methodology is believed to be adaptable for use in seismic evaluation of existing buildings, both ordinary and essential. The importance of this application, particularly in light of the large number of potentially hazardous buildings in the U.S., should not be overlooked.

It is recommended that a field evaluation program be conducted to test and critique the dual-criteria, two-level design methodology, based primarily on that of the Technical Manual 5-809-10-1. The trial design program should include the companion development of supporting risk mapping by the USGS. Consideration should be given the inclusion of several regions in the trial design program. In view of their relevant ongoing building code development programs, New York and South Carolina are considered high priority regions.

Supporting intermediate term research is described in Section 7. This field evaluation program should be conducted as an integral part of the recommended advanced studies.

5.4 The Long Term

As indicated in Chapter 3, the anticipated trend in codified practice will be towards more explicit nonlinear analysis. This has interacting implications with respect to both structural analysis and seismic hazard analysis.

Nonlinear Spectra

There are a number of ways in which nonlinear effects can be incorporated. One approach, which should be further developed, is that suggested in TM 5-809-10-1.

Another promising approach is hazard mapping related to nonlinear response of simple systems. In effect, mapping of nonlinear spectra takes into account the effects of earthquake duration, frequency content and energy levels. Nonlinear spectra for ductility demand or hysteretic energy, are different in form and magnitude from linear response spectra, and their coordinates have different attenuation properties. In addition, the spectra depend on the mechanical properties of the system studied.

Work by *Sewell* (1988) suggests the form of nonlinear spectra for simple damage indicators and indicates alternative relationships for ductility demand. Hazard maps yielding design force levels required to provide specified probabilities of exceeding specified ductility demand have been established. Similar work by *Turkstra and Tallin*(1988) suggests that nonlinear demand spectra have a characteristic form described by parameters that can be mapped directly from measured records.

The geosciences community should be asked to provide hazard maps for nonlinear spectral ordinates corresponding to specified return periods. These maps should be drawn for a standard structure such as a single degree of freedom elasto-plastic system.

On a research level, the effects of duration on multi-degree of freedom systems have been shown to include major changes in response patterns including the possibility of domination by torsional modes. These effects should be investigated in detail.

Soil Amplification

Site-dependent soil amplification factors require further refinement. Soil amplification factors that depend on the ratio T/T_s have been replaced by a step function that relies on a description of the soil profile at the site[7]. The primary reason for this change was that T_s was difficult to predict reliability. However, the ability to identify amplification potential for specific sites has increased. We recommend that improved site amplification factors be developed that relate more closely to soil stratigraphy and measurable soil properties. In urban areas, such properties could be mapped based on existing data and made available for designers.

Time History Analysis

There is a clear trend towards the use of earthquake time histories in direct dynamic analysis of nonlinear systems. Such analysis is now required in Japan for certain buildings and is used in the design of off-shore structures.

To perform such analysis, a set of uniform hazard ground motion input models must be provided by the seismological community for each site. These motions model earthquake frequency content and duration with specified return periods.

Soil-Structure Interaction

Improved analytical techniques will allow for soil-structure interaction to be economically considered in the analysis of structures. As simplified soil-spring models become available, codes should allow consideration of soil-structure interaction by publishing acceptable analytical procedures.

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[7] T_s is the fundamental period of a site.

SECTION 6

EFFECTS OF LOCAL CONDITIONS

This section addresses: (1) the definition of a reference site condition for ground motion mapping; and (2) site modification factors or methods to obtain the response of other site conditions.

6.1 Reference Site Condition

A major requirement is to be clear as to the site condition for which the ground motion parameters are mapped, i.e. to agree upon a satisfactory definition of outcropping "rock" or "hard soil" applicable nationwide. Consensus was not reached at the Workshop regarding a definition for a reference site condition.

Because of the availability of published response spectral attenuation relationships for firm, relatively deep soils, it is suggested that mapping be made for this soil site condition in addition to mapping for a hard rock site condition velocity (shear velocity of at least 3,200 m/s).

6.2 Site Factors for Lateral Force Coefficients

Short Term

It is recommended that the general approach of having a set of soil categories with corresponding site amplification factors relative to rock be used. The four definitions of soil categories in the NEHRP provisions and the UBC are subject to possible differences in interpretation, but they provide a useful starting point. Attempts should be made to better define the soil categories, including shear wave velocities and velocity contrasts. Because of the existence of relatively shallow, high-velocity-contrast sites in the EUS, work should be done to establish appropriate site definitions and factors for this condition.

Long Term

For the long term, it is hoped that most cities and regions will have been microzoned, so that the need for soil factors based upon the present four soil categories will have been minimized. However, since there will inevitably be areas not yet microzoned, "standard soil categories" will still be necessary. It can be anticipated that the categories will be altered somewhat from those now in use, as more experience is gained with these definitions nationwide. Within a given soil category, it is expected that site amplification factors will vary as a function of structural period or period ranges. Site factors might also vary as a function of ground motion amplitude, due to nonlinear ground response phenomena.

It can also be anticipated that factors covering the influence of topographic features and two-and three-dimensional sedimentary basin effects will also be developed.

6.3 Modifying Response Spectra and Ground Motions

Short Term

The use of empirically based spectral adjustment factors to obtain spectra for soil profiles other than the reference rock site condition is recommended here for the short term, in the belief that the practice of making theoretical ground response analyses is not yet well agreed upon or specified. There do exist frequently-used techniques for computing site effects when earthquake motions are specified either by response spectra or by time series. However, there remain some doubts and arguments concerning these techniques. Indeed, seismologists and geotechnical engineers still disagree as to how important nonlinear effects are.

At the same time, it is recognized that the category of relatively thick soft soil (S4 condition in UBC and NEHRP provisions) represents a special case where appropriate empirically-based spectra are not available for the wide range of soil profiles that may be encountered within the S4 definition. For these soils, it is recommended that theoretical ground response analyses be made for longer-period structures which may be particularly vulnerable to ground motions on such soils. The category of soil sites having high velocity contrast with underlying rock also suffers from a lack of recorded data, and ground response analysis should be considered to supplement empirical data for these profiles.

Long Term

By the year 2000, with development of user-friendly software and a sufficient educational effort nationwide, it should be feasible to require theoretical amplification analyses for establishing the effects of local site conditions. It will be necessary to develop clear specifications (or certainly at least guidelines) concerning the methodology for performing these analyses and the substantiation of the results by recorded strong motion data. It is expected that analyses for topographic effects and two- and three-dimensional sedimentary basin effects will be necessary in some cases.

In making these analyses, it will be very important to recognize that the reference rock ground motion is given for a flat outcropping condition and to account for the modification to this motion where rock is overlain by soil. Otherwise, the influence of the soil profile may be overestimated.

As a result of both an expanded empirical data base and generic theoretical analyses, it is also expected that site amplification factors as a function of generalized site characteristics and ground motion intensity will become better established.

6.4 Soil Liquefaction

Liquefaction and related ground failure have been documented in both the eastern and western US. Preliminary results suggest that for an earthquake of a given magnitude, liquefaction occurs at greater horizontal distances from a source in the EUS than in the WUS. This is not surprising considering the decreased attenuation in the EUS.

The higher frequency content in the EUS results in an increased number of strain cycles. Moreover, the large impedance contrasts between soft sandy soils and their substrata often encountered in the EUS further increase the strain levels in the soils. This combination of high cyclic strains and large number of cycles is believed to be a likely contributor to liquefaction at relatively large distances for moderate eastern earthquakes.

There is a wide variety and broad distribution of materials susceptible to liquefaction in the EUS that contribute to the liquefaction hazard. These materials include Quaternary glacial deposits in the Northeast, marine deposits in the Southeast, and fluvial deposits of the Mississippi River Valley. These types of deposits liquefied during moderate to large earthquakes including 1663, 1725 & 1925 Charlevoix, Quebec earthquakes; the 1811-12 New Madrid, Missouri; the 1886 Charleston, S.C.; 1727 Newbury, Massachusetts; and the 1988 Saguenay, Quebec earthquakes.

Regional liquefaction susceptibility maps could be constructed in the short-term; however, liquefaction potential may best be addressed by local site-specific investigations. In the event that cities and regions are microzoned, liquefaction potential can be mapped at that time. However, for areas that will not be microzoned in the near future, a regional liquefaction susceptibility map may be needed to assess the potential for earthquake-induced liquefaction.

SECTION 7

RESEARCH NEEDS FOR GROUND MOTION DEVELOPMENT AND SEISMIC HAZARD MAPPING

As the design of structures to resist seismic forces has developed, some knowledge of the forces imposed has been required. Through measurement of structural reaction as well as free-field motion, an approach to design has come. This has proceeded from primitive to more sophisticated methods. We now are developing or have developed methods which require more trials, more research and more code implementation. To this end research as follows is recommended.

7.1 Seismology and Mapping Group

a. Short term research needs.

1. Treatment of Uncertainty - Research is needed into practical methods of treating uncertainty in seismic hazard estimates, suitable for use in zoning map applications. Should alternative hypotheses for key input parameters be formally treated?

2. Attenuation Relationships - Research should be conducted on appropriate methods of standardizing attenuation relationship for the EUS and WUS to the same "base rock" velocity, and in reconciling eastern and western observations.

b. Long term research needs.

Long-term research needs focus on those investigations that would serve to decrease the degree of subjectivity presently required to derive ground-motion hazard estimates in the Eastern U.S. intraplate tectonic environment. Such needs range over a wide scope of activities that cross a number of disciplines:

1. Better Methods for Defining Earthquake Sources - Most scientists agree that the delineation of earthquake sources should be based on the combination of seismicity and geologic datas. However, the manner in which these data should be used to define source zones is controversial. Improved methods of combining historic and detailed instrumental earthquake data with geologic information are needed.

2. Geologic Studies of Earthquake Sources - Geologic studies of seismogenic faults in the East promise to make substantial contributions to the delineation of earthquake sources. Details on characteristic ruptures and, possibly, on their long-term temporal behavior may be expected from these studies. This optimistic assessment is based on very recent breakthroughs and returns can be expected only in the long-term. For example, recent results suggest that active faults can sometimes be mapped in basement exposed along the surface extrapolation of tightly constrained earthquake ruptures. These faults tend to be subtle features with little accumulated displacement (*Seeber & Armbruster*, 1989). They would probably not have been classified as potential earthquake sources on the basis of conventional recency-of-faulting and cumulative slip criteria.

3. Paleoseismic Studies - The magnitude and recurrence periods of maximum earthquakes from each seismic source are important parameters for estimating hazard, particularly at low probabilities. Few source zones are likely to have experienced maximum earthquakes during historic time. Therefore, it is desirable to extend the seismic record through paleoseismic studies.

Recent studies of geologic features formed during large prehistoric earthquakes in South Carolina and in New England show that the paleoseismic approach can be successful even when applied to earthquakes that have no surface ruptures. Deformation features that are generated by earthquakes can be differentiated from other structures and dated (*Tuttle & Seeber*, 1989). Data of this kind can generate unique constraints on time and size of large prehistoric earthquakes and are expected to eventually become as important to hazard analysis in the East as they have been in the West.

Geologic studies of earthquake-induced soft-sediment deformation not only can identify large prehistoric events, but can also provide information on the behavior of sediments under earthquake load, particularly in cases where ground failure is independently documented. Paleoseismic studies can start in meizoseismal areas where liquefaction and sediment deformation can be inferred from historic accounts or from modern observations. These independent observations can be used to calibrate the paleoseismic approach which can then be confidently applied to other areas.

4. Earthquake Catalogues - Significant improvement in earthquake catalogs is badly needed. Historic earthquakes should be documented with an archival search and source parameters determined by a computer algorithm. This will systematically give location and magnitude with uncertainty estimates. For instrumental earthquakes, location, magnitudes on all relevant scales, and depth should be determined as uniformly as possible through time. In all cases the raw data should be entered into the data base for convenient reanalysis with modified procedures.

5. Seismological parameters keyed to nonlinear response - Current hazard analysis methods are geared toward ground motion or elastic response parameters. As nonlinear analysis methods become more standard, there will be a need to address the probability of exceeding nonlinear response parameters.

7.2 Structural Group

a. For short-term objective:

1. Study and recommend how to use the values coming from the lower probability (longer return period) hazard maps, e.g., from the 0.0005 annual probability map as opposed to the current 0.002 map. In the short-term they must be used in conjunction with current methods and criteria for structural evaluation. As the objective is not to increase the cost of structures, techniques must be proposed and evaluated for use of these higher spectral values in different parts of the country.

2. Study and recommend how to produce a zoning map (with 4 to 6 regions, as now) with these new, lower probability hazard maps. Issues include the parameter to use and the parameter's levels to use for delineating the boundaries.

3. Evaluate the proposed procedures at a set of trial cities by studying the impact on various new and existing structures. This should be done in parallel with the USGS seismic hazard evaluations at those sites. Given current professional activities there, Charleston and New York City are two logical cities. NCEER, SEAOC, and ATC are logical organizations that could be involved.

b. **For intermediate term objectives:**

   1. Study and recommendation of one or more practical methods that approximate non-linear behavior and local ductility demands; examples are those in the Tri-Services Manual (TM 5-809-10-1). These methods may include (a) linear and/or non-linear uniform hazard spectra, (b) increased damping, linear static (pseudo-dynamic) analyses; and/or (c) piece-wise linear, static (pseudo-dynamic) analyses. Study, via "exact" time-history, non-linear analyses the limits of applicability of these methods. When are they even less accurate than current, purely linear code procedures?

   2. For purposes of evaluation for use in practice, prepare a set of trial applications of the dual-criteria, two-level design procedure across a variety of structures (buildings and bridges), a variety of locations, and for both new and existing structures.

   3. Develop and coordinate with USGS any revisions to the hazard mapping process required by the methods above (e.g., increased damping levels, simple adjustments to linear spectra to obtain nonlinear spectra, modified attenuation laws for nonlinear uniform hazard spectra).

c. **Long term research (starting now)**

   1. For nonlinear analysis, structural engineers and seismologists should jointly develop methodologies to establish time histories at any site corresponding to specified hazard levels.

   2. For certain classes of structures, methods to develop uniform damage-based design spectra are required.

   3. Development of improved structural models for nonlinear response should continue.

7.3 Effects of Local Soil Conditions

1. Expand the strong motion recording network with dense arrays and deep borehole stations, installed in different seismotectonic environments. For a successful interpretation of the recordings, it is vitally important that:

- the geology of the region be understood (including topography and geometry of the basin)
- the local soil conditions be determined using state-of-the-art geotechnical (in situ and laboratory) measurements

Attempts should be made to have at least one strong-motion instrument on (soft or hard) flat rock outcrop, for each studied area.

2. Well-documented case histories (from the literature and the dense arrays and deep borehole stations mentioned in [1]) should be used for evaluation/calibration of theoretical methods and procedures for conducting site "amplification" studies. Prediction symposia should be periodically organized to compare and discuss the performance of various methods.

3. Install strong motion instruments (within the aforementioned Task 1 or independently) on very soft clayey and very loose sandy deposits in areas of high seismicity, where the likelihood of a strong ground shaking in the near future is great. (Such a site does not necessarily have to be in the EUS or WUS.) Study the potential effect of nonlinear soil behavior on the record. It would be of great help, of course, if a nearby rock/stiff soil outcrop record or a basement rock/stiff soil record are also obtained as part of this task.

4. Further develop, calibrate, and make widely available computer codes for performing nonlinear-inelastic site response analyses. Synthesize information from previous tasks to resolve the issue of soil nonlinearity during strong shaking.

5. Many techniques exist to make theoretical one-dimensional analyses of site effects. Further studies are needed to synthesize results from these different approaches and to define constraints and guidelines for theoretical site specific studies.

6. Numerous methods currently exist to evaluate the seismic response of two- and three-dimensional geological structures (sedimentary-filled basins, topography, etc.). However, these methods are generally computationally time-consuming and the input parameters are difficult to specify. It is necessary to develop more efficient techniques and user-friendly code that could be used nationwide. Obviously, guidelines concerning necessary parameters and the analyses will have to be clearly specified. Attempts should be made to compare/calibrate with actual records.

7. As noted in Sections 3 and 6, there are a limited number of "standard soil profiles" and corresponding "site factors" now in the codes. These should be reviewed, modified, and added to as appropriate, using empirical data and theoretical considerations and considering possible regional differences in predominant soil and rock conditions. For example, the typical condition in the eastern U.S. of a high impedance contrast between soil and rock should be considered.

SECTION 8

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Workshop on
GROUND MOTION PARAMETERS FOR SEISMIC HAZARD MAPPING

July 18-19, 1989

National Center for Earthquake Engineering Research
State University of New York at Buffalo

AGENDA

Tuesday, 18 July

8:30 Whitman: Introductions, marching orders - 140 Ketter Hall

8:45 Perkins: USGS short-term program; presentation of seismic hazard assessment for selected area of East

9:00 Singh: SEAOC viewpoints and perspectives

9:15 Whitman: questions, discussions, further marching orders

9:30 Break

9:45 Simultaneous meetings of Working Groups A, B and C
Group A - 140 Ketter Hall
Group B - 210 Ketter Hall
Group C - 217 Bonner Hall

12:00 Working lunch - 140 Ketter Hall
Demonstration: Lamont-Doherty Ground Motion Data Base - 144 Ketter Hall
Tour: Seismic Simulator Laboratory - Ketter Hall

1:00 Plenary session: preliminary conclusions/recommendations from Working Groups A, B and C. General discussion. Revised marching orders.

3:00 Break

3:15 Continued simultaneous meetings of Working Groups A, B, C, D and E

Evening - Buffalo Marriott

7:00 - 7:30 PM Cash bar - Ballroom 2

7:30 - 9:30 PM Dinner - Ballroom 2

Wednesday, 19 July

8:30 Plenary session: revised recommendations. Discussion as necessary.

9:30 Meeting of all groups as appropriate
  Group A - 140 Ketter Hall
  Group B - 210 Ketter Hall
  Group C - 217 Bonner Hall

10:00 Coffee, etc. available

11:00 Deadline for revised drafts from several groups. Plenary session for presentation and discussion of conclusions, recommendations. Revised marching orders.

12:00 Working lunch available - 140 Ketter Hall

2:00 Deadline for penultimate drafts from several groups.
Plenary session to discuss and approve final draft of report.

3:30 Final editing session for all groups

4:00 Closure - 140 Ketter Hall

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GROUND MOTION PARAMETERS FOR SEISMIC HAZARD MAPPING

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Participants

Mr. J. Armbruster, Staff Associate 914-359-2900
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. Gail Atkinson 519-741-0757
Consultant
125 Dunbar Road South
Waterloo, ON N2L 2E8
CANADA

Dr. Bernice Bender 303-236-1589
U.S. Geological Survey
OSM, Room 446
Mail Stop 966
Denver, CO 80225

Dr. Ian G. Buckle 716-636-3391
Deputy Director
National Center for Earthquake Engineering Research
105 Red Jacket Quadrangle
State University of New York at Buffalo
Buffalo, NY 14261

Professor C. Allin Cornell 415-854-8052
110 Coquito Way
Portola Valley, CA 94025

Mr. Paul Friberg 914-359-2900
Staff Associate
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Mr. Jean-Christophe Gariel Post-Doctoral Research Scientist Lamont-Doherty Geological Observatory of Columbia University Palisades, NY 10964	914-359-2900
Dr. George Gazetas, Professor Civil Engineering 137 Ketter Hall State University of New York at Buffalo Buffalo, NY 14260	716-636-3634
Dr. Peter Gergely Professor, Structural Engineering School of Civil Engineering Hollister Hall Cornell University Ithaca, NY 14853	607-255-4217
Subhash C. Goel, Professor Civil Engineering Department The University of Michigan Ann Arbor, MI 48109	313-764-8419
Dr. Jim Harris J.R. Harris & Company Suite 770 1580 Lincoln Street Denver, CO 80203-1509	303-860-9021
Dr. Susan Hough Associate Research Scientist Lamont-Doherty Geological Observatory of Columbia University Palisades, NY 10964	914-359-2900
Dr. Howard H.M. Hwang Associate Research Professor Center for Earthquake Research and Information Memphis State University 3890 Central Avenue Memphis, TN 38152	901-678-2007

Mr. O. Allen Israelson
Building Seismic Safety Council
4th Floor
1201 L Street, NW
Washington, DC 20005
Work: 202-289-7800
Home: 301-598-2901

Dr. Klaus Jacob
Senior Research Scientist in
Seismology and Tectonics
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964
914-359-2900 (ext. 440)

Dr. E.V. Leyendecker
U.S. Geological Survey
OSM, Room 446
Mail Stop 966
Denver, CO 80225
303-236-1601

Dr. Charles Lindbergh
Professor and Head
Department of Civil Engineering
The Citadel
Charleston, SC 29409-0225
803-792-5083 (ext. 7676)

Dr. John B. Mander
Assistant Professor
Civil Engineering
136 Ketter Hall
State University of New York at Buffalo
Buffalo, NY 14260
716-636-3634

Guy J.P. Nordenson
Ove Arup and Partners, Ltd.
260 5h Avenue
New York, NY 10001
212-779-2221

Mr. Bruce C. Olsen
Consulting Engineer
Suite #1420
1411 4th Avenue
Seattle, WA 98101
206-624-7045

Dr. David M. Perkins 303-236-1616
U.S. Geological Survey
OSM, Room 446
Mail Stop 966
Denver, CO 80225

Mr. Maurice Power 415-957-9557
Geomatrix Consultants, Inc.
One Market Plaza
Spear Street Tower, Suite 717
San Francisco, CA 94105

Dr. Lawrence D. Reaveley 801-486-3883
Vice President
Reaveley Engineers & Associates, Inc.
1515 South 1100 East
Salt Lake City, UT 84105

Dr. Albert Rogers 303-236-1585
U.S. Geological Survey
OSM, Room 446
Mail Stop 966
Denver, CO 80225

Mr. Christopher Rojahn 415-595-1542
Executive Director
Applied Technology Council
Suite 275
3 Twin Dolphin Drive
Redwood, CA 94065

Mr. Leonardo Seeber 914-359-2900
Associate Research Scientist
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. J.P. Singh, President 415-222-5700
Geospectra
Suite 213
3095 Atlas Road
Richmond, CA 94806

Dr. Paul Thenhaus U.S. Geological Survey OSM, Room 446 Mail Stop 966 Denver, CO 80225	303-236-1610
Dr. Carl J. Turkstra, Professor Civil & Environmental Engineering Polytechnic University 333 Jay Street Brooklyn, NY 11201	718-260-3059
Ms. Martitia Tuttle Staff Associate Lamont-Doherty Geological Observatory of Columbia University Palisades, NY 10964	914-359-2900
Dr. Russell Wheeler U.S. Geological Survey OSM, Room 446 Mail Stop 966 Denver, CO 80225	303-236-1592
Dr. Robert V. Whitman, Professor Department of Civil Engineering Room 1-342 Massachusetts Institute of Technology 77 Massachusetts Avenue Cambridge, MA 02139	617-253-7127
Mr. Joseph Zona Simpson, Gumpertz and Heger 297 Broadway Arlington, MA 02174	617-643-2000

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