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Some notes concerning prediction of ground motions for GSHAP

David M. Boore([1]) **and Nick N. Ambraseys**([2])
([1]) U.S. Geological Survey, Menlo Park, CA, U.S.A.
([2]) Imperial College, London, U.K.

Abstract
We confront key issues concerning the derivation of attenuation laws, the measure of ground motion as function of magnitude and distance, for the implementation of GSHAP: the availability of strong motion recordings, data bases and ancillary information on seismic sources and sites on a global scale, the use of regional attenuation laws in several areas of the globe and their applicability in a global program, how to assess hazard in areas where strong ground motion recordings are not available, the use of intensity data, the preferred parameters to be used in mapping seismic hazard.

1. Introduction

Underlying any quantitative evaluation of seismic hazard is a mean for obtaining an estimate of ground shaking at a given distance from an earthquake of specified magnitude. The usual means to obtain these estimates is to use equations giving some measure of ground motion as a function of magnitude and distance (and sometimes other predictor variables as well). These equations, usually referred to as attenuation relations, have been developed for few parts of the world. Obtaining realistic estimates of ground motions in other regions is a major challenge that must be met if GSHAP is to be a success.

To help focus discussion, we structure the paper around several questions related to estimating ground motions.

2. What strong motion recordings and ancillary information about sources and sites are available on a global scale?

Strong motion recordings form the absolute core of any attempts to estimate ground shaking. Many strong motion recordings have been obtained, but full use of these data is hampered by problems of access and by lack of essential information regarding the earthquake sources and the local geologic conditions. Data banks – repositories of digitized recordings, but without special attention to uniformity of processing or accuracy of ancillary information – have been established by a number of organizations. A partial list includes those published in the United States by the U. S. Geological Survey (a recently-published CD-ROM of digitized strong motion accelerograms from north and central American earthquakes from 1933 through 1986), the National Geophysical Data Center of the National Oceanographic and Atmospheric Administration [SMCAT (Row, 1990)], the National Center for Earthquake Engineering Research [STRONGMO (Friberg and Susch, 1990)], in the United Kingdom by Imperial College (Bommer, 1991), and in Canada by McMaster University; in addition, work is in progress in Central and South America (F. Güendal, oral commun., 1992; A. Giesecke, written commun., 1992). No organization has been able to collect a complete set of recordings (this is impossible even within the same country or state, given the diverse groups operating strong motion recorders and the lack of cooperation by some of the responsible individuals). Data bases – collections of uniformly processed records, along with the supporting tectonic, seismological, and geologic information, carefully sifted and windowed by experienced researchers – are much less common (the University of Southern California has a data base of uniformly processed data (EQINFOS (Lee and Trifunac, 1987)). Indiscriminate use of the relatively easily obtainable data from data banks has the danger that the resulting estimates of ground motion may be subject to so much uncertainty as to be worthless.

It cannot be emphasized too strongly that even the most basic information, such as the size of an event as measured by various magnitudes, and the geometry and spatial location of the rupture surface (or even the hypocenter), are often poorly known. Strong motion recorders are often deployed, maintained, and their data processed by people with inadequate knowledge and appreciation for the seismological aspects of the data. As an example, the distance from station 2 to the rupture surface of the 1966 Parkfield, California, earthquake has been assumed by many authors to be less than 0.3 km, on the basis of ground cracks along the San Andreas fault near the station. On the other hand, from a seismological analysis of relative arrival times of phases on the various strong motion recordings, Lindh

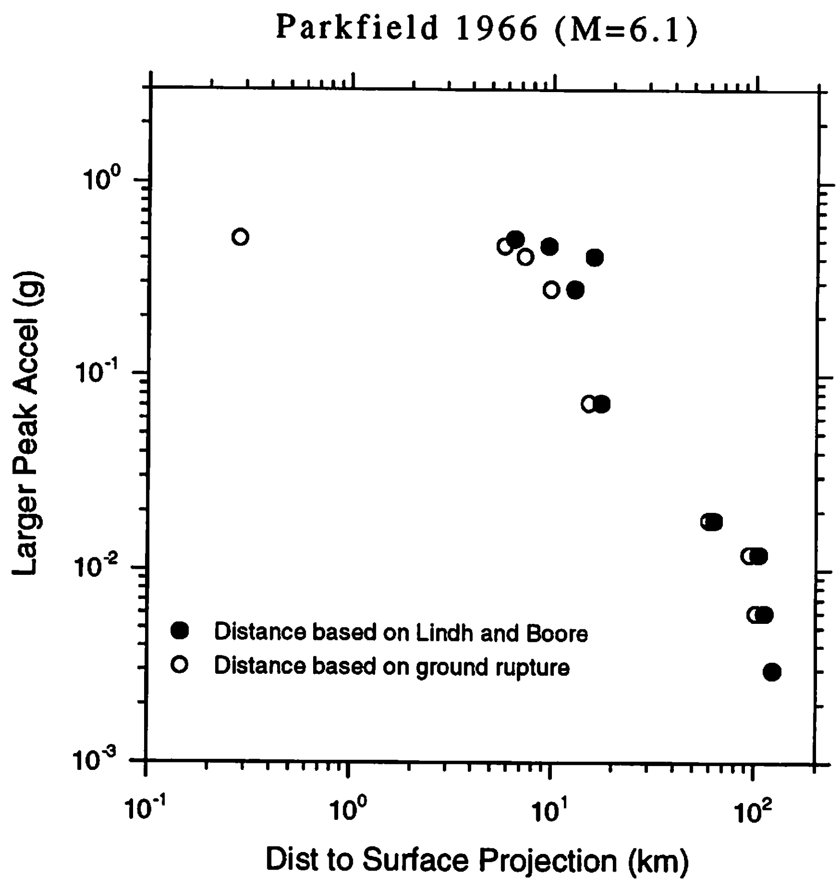

Fig. 1. Recordings for 1966 Parkfield earthquake, with two assumptions as to the location of the rupture surface.

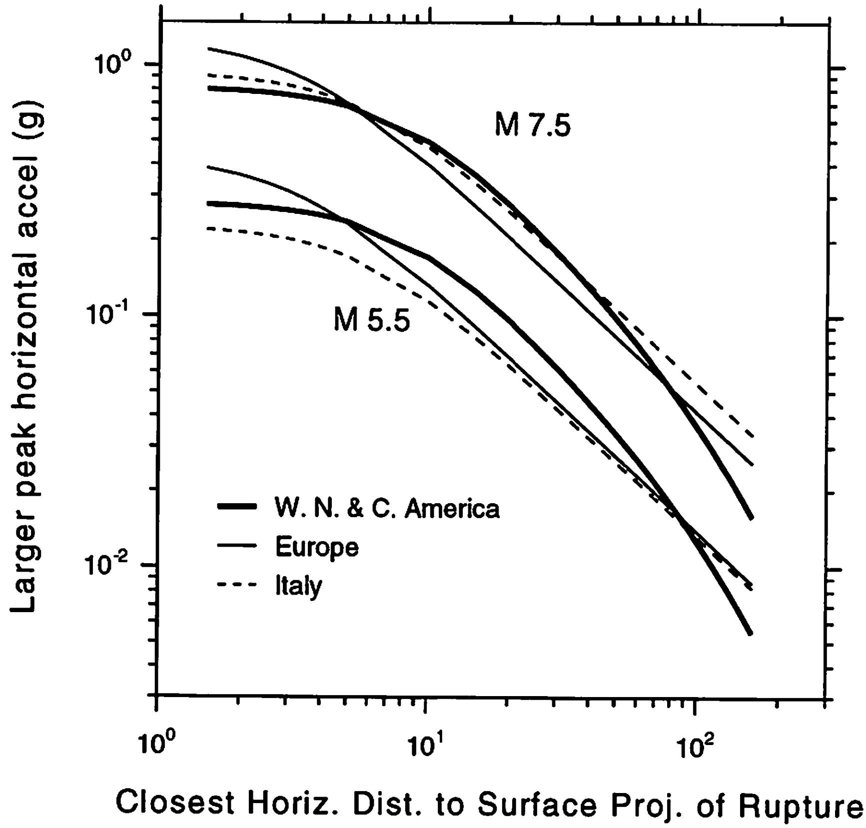

Fig. 2. Peak acceleration attenuation for western North and Central America (Joyner and Boore, 1982, 1988), Italy (Sabetta and Pugliese, 1987), and Europe (Ambraseys and Bommer, 1991).

and Boore (1981) argue that the main rupture terminated some 6 km from the station. The distance one assigns to the station 2 recording has a significant influence on the close-in behavior of attenuation curves (fig. 1).

As another example, the 1979 Imperial Valley earthquake contributed vital information for constructing attenuation curves because it was well-recorded at close distances and was a good-sized event. Magnitudes assigned for the event include 6.5 (moment magnitude) and 6.9 (surface wave magnitude). The magnitude assigned may have a substantial impact on the scaling of ground motion with source size at a fixed distance. As a final example, the Cape Mendocino region of California is one of the most seismically active areas in the United States, and at least 18 earthquakes have been recorded over the last 5 decades in Ferndale. Almost none of these recordings can be used for ground motion estimation, however, for the locations of the associated earthquakes (many of which are offshore) are poorly known (with location uncertainties of more than 20 km). A welcome exception was the recent Petrolia earthquake, which had an onshore epicenter and adequate recordings to locate the aftershocks.

What might GSHAP accomplish? A specific program to establish data banks and data bases in the regional centers would be very useful. Presumably, regional centers would be well positioned to establish contacts with sources of records and could obtain site information via special studies (source information for past and future earthquakes might be difficult to obtain, but plans can be made to obtain the necessary information in future earthquakes. One useful thing is simply to retrofit existing accelerographs with receivers so that absolute time is available on future records).

Much work remains to be done for the retrieval and uniform processing of existing analogue records in many parts of the world. Although a great deal of effort and funds have been invested world-wide in recording strong ground motions, the work of bringing all the available records together and processing the data in a uniform manner has yet to be carried out. This lack of accessibility denies the earth scientist and engineer the possibility of utilizing this invaluable resource. The technology of strong motion recording and processing has advanced considerably, but the availability of reliable and uniformly processed digital data from earthquakes of the last two decades is still relatively poor, particularly for areas such as Asia and Europe.

3. Are existing attenuation relations adequate for mapping seismic hazards on a global scale?

The answer to this question depends on how «adequate» is defined. For example, fig. 2 shows peak acceleration for magnitude 5.5 and 7.5 earthquakes for western North and Central America (Joyner and Boore, 1982 and 1988), Italy (Sabetta and Pugliese, 1987), and Europe (Ambraseys and Bommer, 1991). Some readers might draw the conclusion from these figures that overall the curves agree quite well

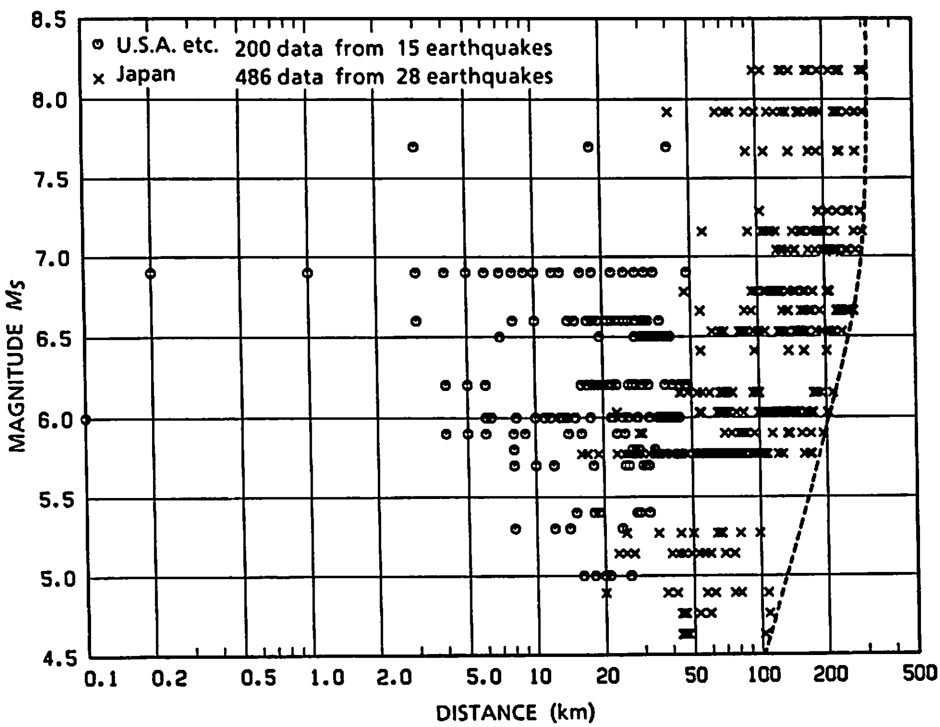

Fig. 3. Magnitude-distance for acceleration (from Fukushima and Tanaka, 1990). Points from Japan are given by «x»es and those from other parts of the world (primarily California) by circles. Notice the lack of overlap.

with each other, particularly in view of the standard deviation of over 0.2 log units associated with the prediction of a single observation. The large scatter might completely mask the likely differences that exist amongst the various geologic regions of the globe. On the other hand, the maximum difference between the curves (which represent median values of acceleration) is almost a factor of 2, which might have a large impact on hazard maps.

In the derivation of many local, regional, or «national» attenuation laws, use is often made of all available data , regardless of their quality and the homogeneity and range of variables, with the result that little confidence can be placed on the resulting attenuation laws. This uncritical derivation of attenuation laws contributes to the proliferation of local attenuation laws of ephemeral validity which confuses the uninitiated engineer or gives a wide choice to the engineer for the selection of convenient design ground motions. The examples in the figure were specifically chosen because care and thought went into the selection of the data used to derive the relations.

Even if exellent data bases existed in various regions (*i.e.*, all recordings were available and had been uniformly processed, and source and site information had also been obtained), different biases in the distribution of the data and differences in the regression analysis can lead to apparent differences in the curves that may not exist. Different data sets may lack information from large events, especially at close distances, or the range of magnitudes may be narrow or derived from a kaleidoscope of magnitude scale. As an example, consider two figures from Fukushima and Tanaka (1990). The first (fig. 3) shows the magnitude and distance distribution of data from Japan and other countries (primarily from the State of California in the U.S.).

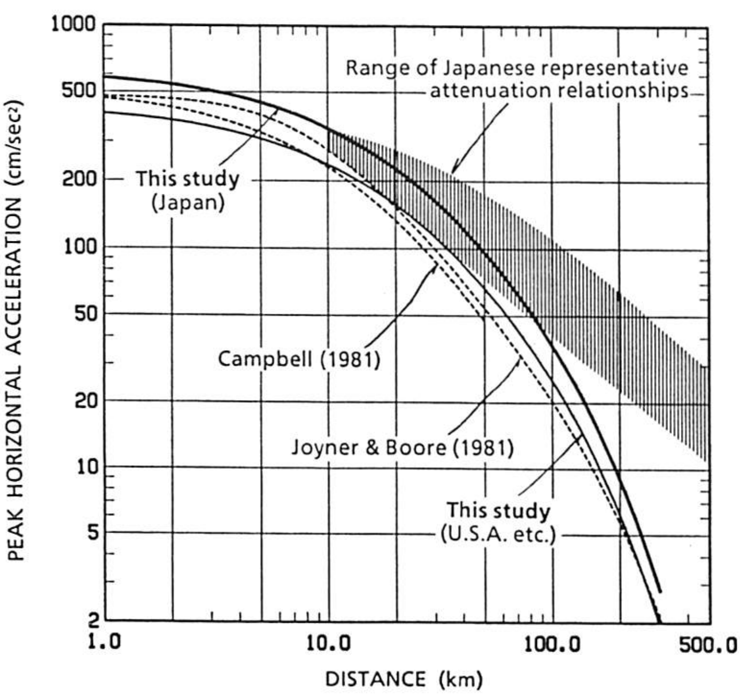

Fig. 4. Peak acceleration relations (from Fukushima and Tanaka, 1990). The shaded area represents the range of values for previous estimates of attenuation in Japan, using similar data to that used by Fukushima and Tanaka in deriving the curve labeled «This study (Japan)».

Notice that few data are available close to large earthquakes, and that the magnitude-distance distributions for Japan and the other countries form almost disjoint sets (the distance is hypocentral distance for Japan and closest distance to the rupture surface for the other data; the magnitude for the Japanese data have been converted from M_J to M_S). This difference is largely due to the different tectonic regimes (shallow strike slip vrs subduction with a scattering of crustal earthquakes). This difference in distribution of data makes it difficult to compare attenuation curves between various regions.

The second figure from Fukushima and Tanaka (fig. 4) compares their new relations with those from previous studies in Japan (and also with those from other parts of the world; for the reasons stated above, these comparisons may not be very meaningful).

According to Fukushima and Tanaka, the large and systematic differences between the previous studies and their new results are a consequence of the strong correlation between magnitude and distance; uncertainties in magnitude may be mapped into a bias in the attenuation coefficient. They have used a two-stage regression scheme that helps to decouple any tradeoffs that might occur because of the correlation (the same thing can be accomplished with a properly weighted, single-pass regression).

What can GSHAP do to obtain reliable attenuation relations? Probably the most important is to build a good data base. The analysis procedures are fairly straightforward, and attenuation relations can be derived in short order if the basic data are available. Most regions for which adequate data might be available (even if it has not currently been brought into a good data base) have local experts who are capable of deriving the attenuation relations. The real problem is what to use for ground motion attenuation in regions for which adequate strong motion data are not available. This is the subject of the next section.

4. What can be done in regions for which adequate data are not available?

Two situations present themselves. Data close to large earthquakes is almost universal-

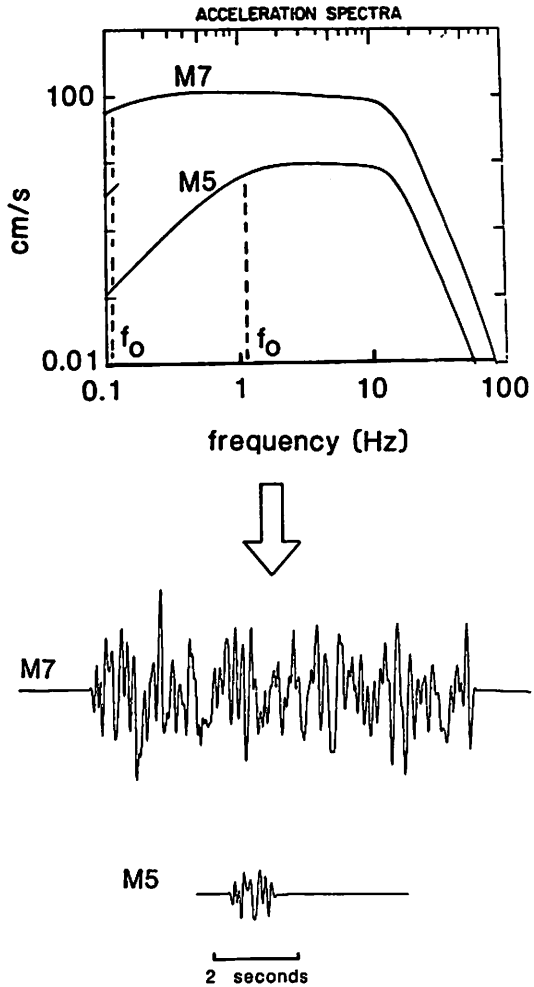

Fig. 5. Basis for stochastic model (from Boore, 1989). Radiated energy described by the spectra in the upper part of the figure is assumed to be distributed randomly over a duration equal to the inverse of the lower frequency corner (f_0). The time series is one realization of the random process for the actual spectra shown. The levels of the low frequency part of the spectra are directly proportional to the logarithm of the seismic moment and thus to the moment magnitude. Various peak ground motion parameters (such as response spectra, instrument response, and velocity and acceleration) can be obtained from the suite of time series or more simply by using random vibration theory, working directly with the spectra. The examples in this figure came from an actual simulation and are not sketched in by hand.

ly lacking, even in those regions for which numerous strong motion recordings are available (*e.g.*, see the magnitude-distance distribution presented earlier). Second, a number of regions with a demonstrated history of seismic activity have no modern recordings of damaging earthquakes. In both cases, some extrapolation from the data base of strong motion recordings is needed to make estimates of ground motions. This is often done by a combination of theoretical calculations and by analogy to tectonically similar regions for which data are available.

A method that takes advantage of seismological information using smaller events has been developed in recent years and has met with some success in predicting a wide range of ground motion parameters. The essence of this method is to use whatever seismological information is available to specify the spectrum of the radiated energy, and then use the assumption that this energy is distributed in a random fashion over a duration related to the source duration and the propagation path to derive a variety of ground motion estimates (fig. 5 shows the spectra and simulated time series for an actual application).

Information about source scaling can be readily used, and this information can be obtained from the relations between various magnitudes and special studies (sometimes using teleseismic recordings) of the source spectra of earthquakes in a region (fig. 6 shows estimates of high frequency spectral level derived for a number of intraplate earthquakes from a variety of studies; with the exception

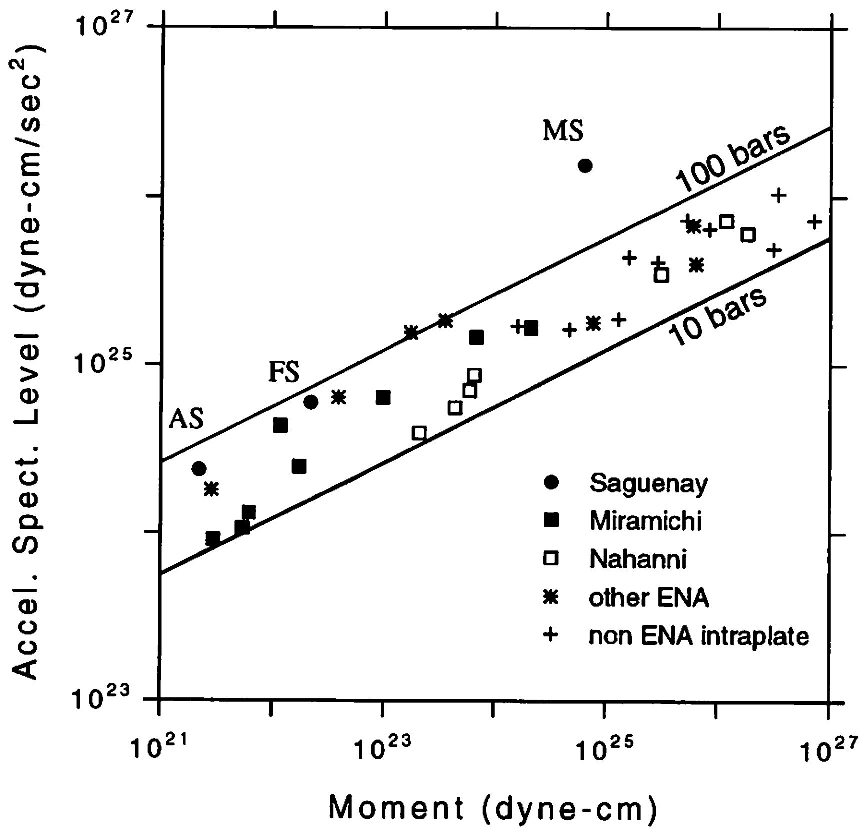

Fig. 6. Scaling of high frequency source spectral level for intraplate events (from Boore and Atkinson, 1992).

of the Saguenay mainshock, constant stress scaling is implied).

Information about attenuation can be provided by studies of motions from more numerous, smaller earthquakes. a number of such studies have been made, and in many places data for additional studies can be gathered in the time frame of the IDNDR. GSHAP should promote the collection of such data. As an example of possibly relevant studies, fig. 7 shows the attenuation correction for the specification of M_L magnitude.

The curves were made by performing regression analyses on peak amplitudes measured from recordings on Wood-Anderson torsion seismometers (or surrogates thereof). For comparison, the attenuation of peak acceleration from western North America is shown by the filled circles. The curves were normalized to unity at 20 km.

5. What about intensity?

Intensity data have the potential for significantly augmenting instrumental recordings of ground motion. Unfortunately, for a variety of reasons the ground motions predicted from in-

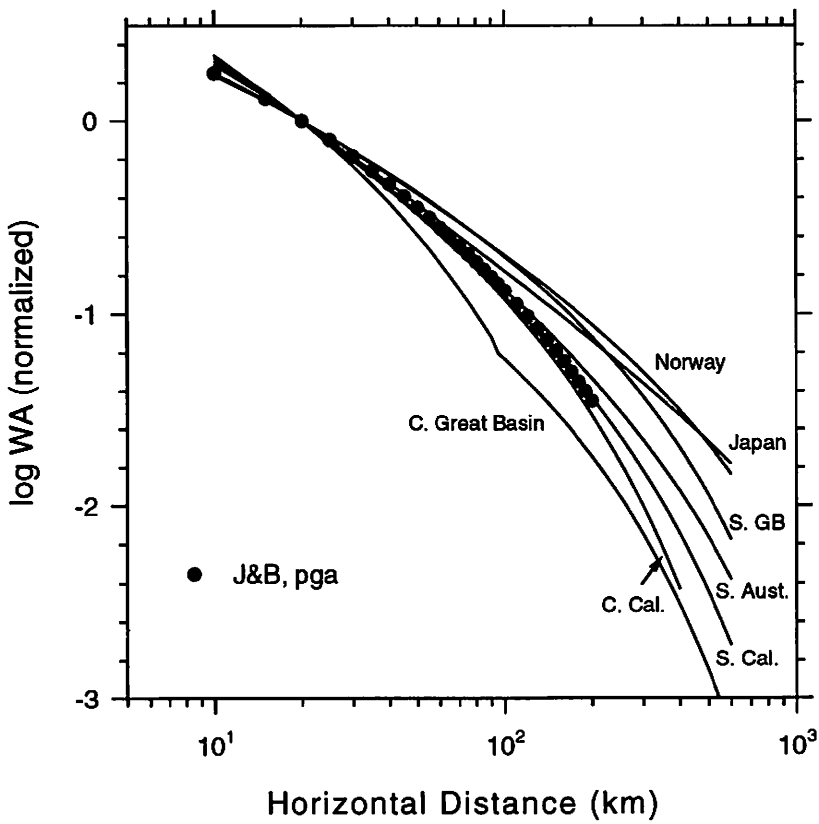

Fig. 7. Attenuation of peak motions from Wood-Anderson seismographs, compared with the Joyner and Boore (1982) peak accelerations. Central California (C. Cal.) from Bakun and Joyner (1984); Southern California (S. Cal.) from Hutton and Boore (1987); Central Great Basin (C. Great Basin) from Chavez and Priestley (1985); Southern Great Basin (S. GB) from Rogers *et al.* (1987); South Australia (S. Aust.) from Greenhalgh and Singh (1986); Japan from Y. Fujino and R. Inoue (written communication to DMB, 1985); Norway from Alsaker *et al.* (1991).

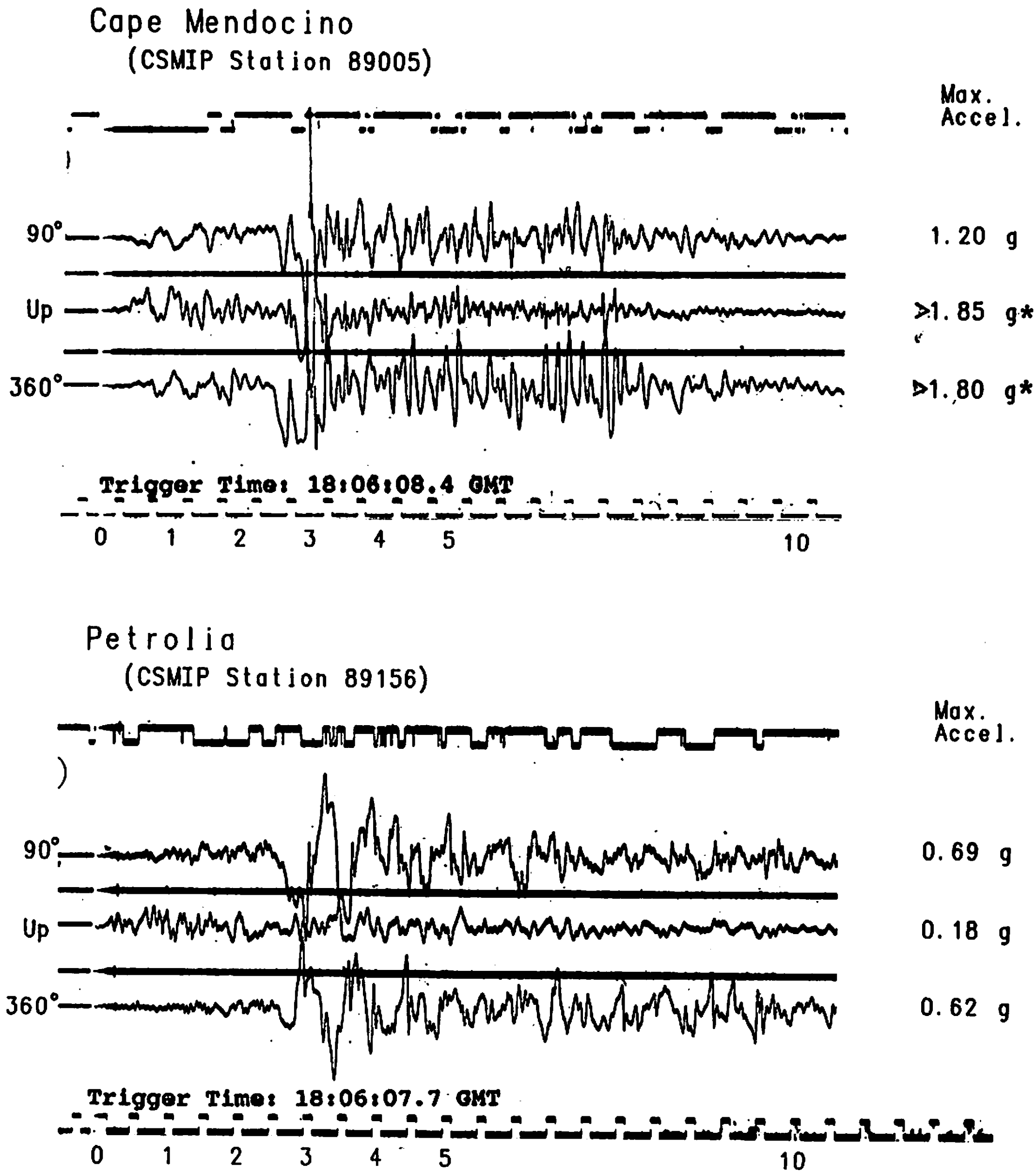

Fig. 8. Accelerograms at two stations close to the surface projection of the rupture surface of the 25 April 1992 Petrolia, California, earthquake (from Shakal *et al.*, 1992).

tensities can be unreliable, and sophisticated analyses are needed in making the correlations between intensities and ground motion (*e.g.*, Veneziano, 1988). Macroseismic data, in terms of homogeneously-defined isoseismals, may be used, however, to assign magnitudes to their causative events (*e.g.*, Johnston, 1992). This can be done be calibrating sets of isoseismals against magnitudes, a method that gives stable results but which must be applied to well-defined tectonic environments rather than to global conditions (Howell and Schultz, 1975; Ambraseys, 1985). Having assessed the size of the earthquakes in terms of a magnitude, one can use an appropriate attenuation equation to estimate ground motions.

The derivation of region-specific calibration functions between magnitudes and their corresponding sets of isoseismals needs internally consistent data on both; the isoseismal contours must be drawn on maps of intensity points assigned from examination of primary historic macroseismic information, and the magnitude data must be uniformly re-evaluated.

6. What ground motion parameters should be mapped?

The most used parameter has been peak acceleration, but the trend seems to be to move away from this in favor of parameters that are more closely related to the frequency

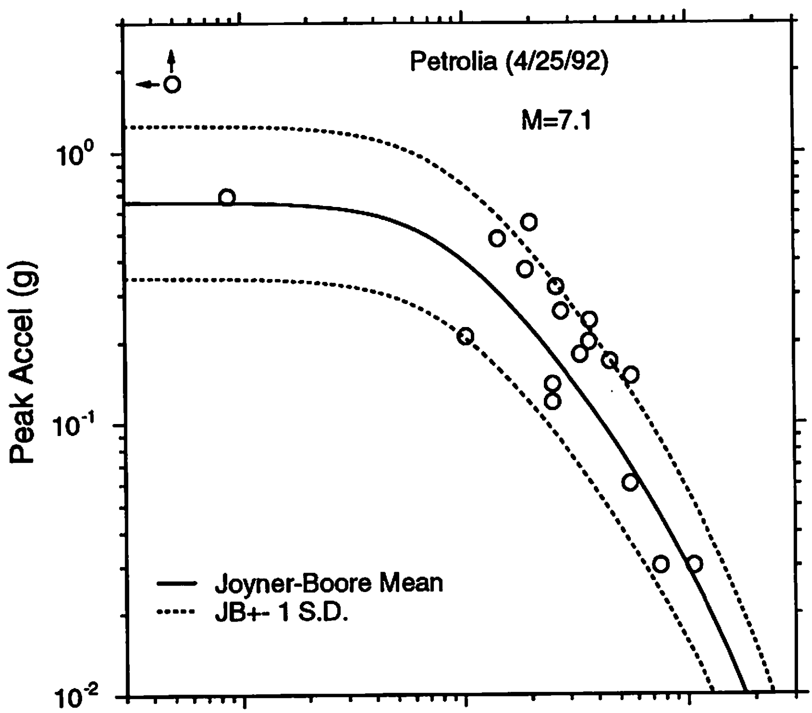

Fig. 9. Comparison of peak accelerations from the Petrolia earthquake with those predicted by the empirically-based equations of Joyner and Boore (1982).

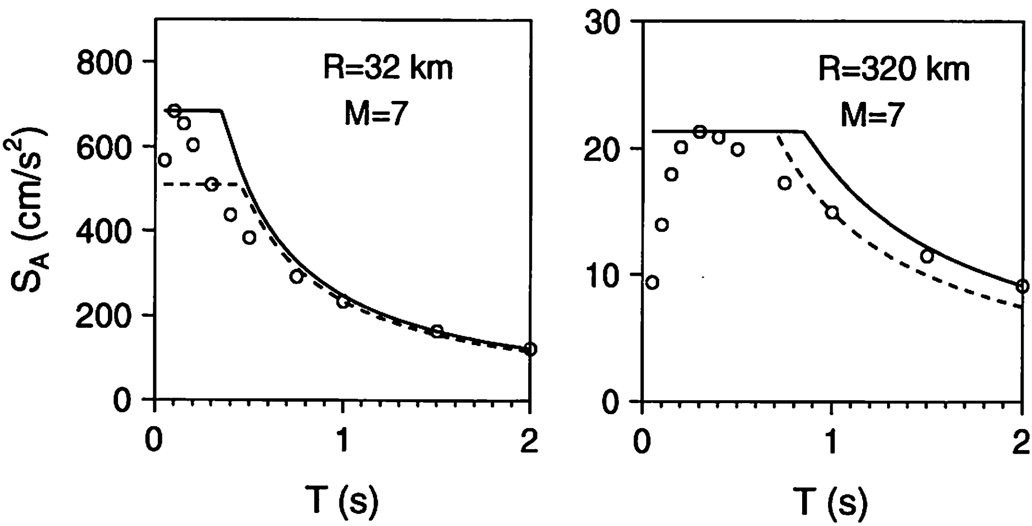

Fig. 10. Comparison of simulated pseudoacceleration spectra (circles) and approximations based on spectral ordinates at fixed periods of 0.3 and 1.0 sec (dashed lines) and on the largest values (solid lines) (from Boore and Joyner, 1991).

content of the ground motion. A good example of how peak acceleration can be very misleading, shown in fig. 8, is given by the Cape Mendocino recording of the recent Petrolia earthquake; this record contains a single short duration spike – on the order of 0.1 to 0.2 sec – in excess of 1 g on all three components.

Although a digital version of the record has not been made available at the time of this writing and therefore it is not possible to state with certainty what the response spectrum would be, it is unlikely that the spike could have had much influence on periods of 0.5 seconds or longer. Figure 9 shows that the peak accelerations from all but the closest station are in good agreement with those expected from the analysis of peak accelerations from previous earthquakes.

A new generation of hazard maps has been prepared by the USGS for use in a new national building code (Algermissen *et al.*, 1991). The parameter mapped is the response spectra at 0.3 sec and 1.0 sec periods for 5 percent damping. This is a convenient 2-parameter specification of the total response spectrum. The actual acceleration response spectrum is approximated by the intersection of a constant line at level $S_a(0.3)$ and the hyperbola given by $2\pi S_v(1.0)/T$ (additional conservatism is added into the long period response in the construction of the design spectrum). From this prescription, response spectra can be easily computed for a structure of any period, and these spectra will be close approximations of the spectra that would be obtained by the evaluation of the complete response spectrum.

This prescription can lead to underestimates of response values in those cases where the surficial rock is very competent, allowing high-frequency motions to be propagated with little attenuation. This situation may exist on hard-rock sites in parts of northeastern North America. To allow for such cases, the largest values of the pseudoacceleration (S_{amax}) and pseudovelocity (S_{vmax}) response in the period range of engineering interest can be used in place of S_a and S_v in the prescription above (Boore and Joyner, 1991). Figure 10 shows a comparison of the two ways of specifying the spectrum, compared with the complete spectrum for sites in northeastern North America.

Given digital data, a few spectral ordinates can be mapped as easily as can peak acceleration, and these ordinates can be related more easily to spectral response at any period, without the problems associated with peak acceleration. We propose that GSHAP downplay the mapping of peak acceleration and use instead a few well-chosen spectral ordinates.

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