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Use of the uniform hazard spectrum in characterizing expected levels of seismic ground shaking

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ABSTRACT

This paper provides an overview of the uniform hazard spectrum in comparison to the traditional scaled spectrum approach, for applications in both eastern and western North America (ENA and WNA). Examples are used to show that a scaled spectrum overestimates linear response for intermediate frequencies for some types of earthquakes, by as much as 300%. The result is that scaled spectra for a constant probability level can be in significant error (100% or more) for some seismic environments. A new algorithm for constructing spectra for building code mapping purposes is proposed. The new algorithm replaces peak ground acceleration and velocity with two spectral parameters ('dynamic acceleration' and 'dynamic velocity'). Spectra constructed by the new algorithm are as simple as scaled spectra, but much more accurate.

INTRODUCTION

Traditional probabilistic seismic hazard studies, following the well-accepted Cornell-McGuire method (Cornell, 1968; McGuire, 1977), have often been used to estimate expected levels of peak ground acceleration (PGA) and velocity (PGV) for a specified probability level. Response spectra for engineering design purposes were then constructed by scaling a standard spectrum (eg. Newmark and Hall, 1982) to the site-specific PGA (and/or PGV) levels. This practice formed the basis for Canadian and U.S. building codes from 1970 through 1990 (eg. Basham et al., 1982).

It has been recognized since the mid-seventies that a more direct route of developing the response spectra for any desired probability (McGuire, 1977), known as the 'uniform hazard spectrum' (UHS) approach, is conceptually superior and less subject to error. The UHS is also based on the Cornell-McGuire approach, but the hazard computations are performed for response spectral ordinates for specified frequencies, rather than for peak ground motion parameters. This eliminates the need to scale

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standard spectral shapes to PGA and PGV. The two processes are compared in Table 1.

Although the UHS method has been available for nearly 15 years, it has not been widely used in standard engineering practice until recently. This is largely because reliable ground motion relations for response spectral ordinates, which are needed for the calculations, have only recently been developed, based on data that did not exist when the concept was first proposed. Within the last 5 years, the UHS method has been applied to a range of facilities in Canada and the U.S. (including dams, nuclear power plants, and offshore structures), and has been recommended as the basis for the next revision of seismic zoning maps for use in building code applications (Whitman, 1989). However it is still unfamiliar to most engineers.

The purpose of this paper is to provide an overview of the UHS in comparison to the traditional scaled spectrum approach, for applications in both eastern and western North America (ENA and WNA).

GROUND MOTION RELATIONS FOR ELASTIC RESPONSE SPECTRA

Ground motion relations provide the mathematical link between the occurrence of earthquakes and the resulting site ground motions. Given a suitable database, ground motion relations can be developed for any parameter of interest, such as PGA, or the maximum response velocity for given frequency values (PSRV). Response spectra convey more information regarding the amplitude and frequency content of the earthquake than does PGA and PGV, and are more directly applicable to dynamic analysis methods. However PGA and PGV were more often used until recently, partly due to the availability of applicable ground motion relations. (Another is the widespread use of empirical design checks which are based solely on PGA.)

In WNA, ground motion relations have been largely based on regression of recorded strong ground motions. Since the late 1970's, the database for these relations has greatly improved, to the point that empirical relations for PGA, PGV and PSRV are now reliable except for large earthquakes ($M > 7$) at close distances ($R < 50$ km) (see Joyner and Boore, 1988 for a review of these). It must be understood, however, that such relations provide median or average ground motion levels, and any specific observation may deviate from the relations by a factor of two (about one standard deviation) or more.

More recently, simple seismological models of the earthquake source, in conjunction with random process methods, have been used to derive ground motion relations (eg. Boore, 1983; Atkinson and Boore, 1990) for both WNA and ENA. Comparisons of the theoretical relations with empirically-based relations and actual data have verified the model assumptions for WNA (Boore, 1983) and provided confidence in the applicability of the method. Relations derived for ENA by this method are compared to available data in a separate paper in these proceedings (Atkinson, 1991).

The recent improvement in ground motion relations allows systematic comparison of ENA and WNA earthquakes. Ground motion characteristics for the two regions differ due to the high-frequency enrichment of eastern earthquakes, and differences in attenuation and crustal properties. At frequencies less than 10 Hz, eastern and western PSRV values are comparable at near-source distances, but eastern motions decay more slowly with distance. For frequencies greater than 10 Hz, ENA ground motions are significantly larger than their western counterparts. These differences have been well-substantiated by data.

The concept of using a standard spectral shape for all earthquakes was developed in the 1960's and 1970's from a WNA database, dominated by records of M 6 to M 7.5 at distances of 20 to 40 km. The ground motion relations for elastic response spectra can be used to test the applicability of the scaled spectral shapes to earthquakes of various types. Results of such comparisons (Atkinson, 1989) show that the best agreement is achieved for spectra based on both the PGA and PGV, using the median amplification factors of Newmark and Hall (1982). Obviously, since scaled spectra are simplified versions of actual spectra (eg. two straight lines representing a smooth curve) the agreement between scaled and actual spectra is not expected to be perfect. However, the errors incurred by the use of PGA and PGV to construct the simple bilinear spectrum are surprisingly large for some types of earthquakes. In Table 2, these errors are listed for earthquakes of various types, for several frequencies. (Note: A detailed package of plots from which the tables were constructed is available to the interested reader; a sample is given in Figure 1 for illustration.) To estimate these errors, 'actual' response spectra (median observations, based on the relations of Joyner and Boore, 1982, for WNA, and Atkinson and Boore, 1990, for ENA) were compared to the corresponding 'standard' spectra (obtained by scaling PGA and PGV, also from the relations of Joyner and Boore, and Atkinson and Boore, by the median amplification factors of Newmark and Hall, 1982). In these comparisons, and for the remainder of this paper, all ground motion values are median horizontal component values for rock site conditions; spectral response parameters are for 5% damping.

The PGA-PGV scaled spectrum approach works well for ENA events of M5 to M6 at frequencies above 1 Hz. (Caution: spectra for ENA based on PGA alone - not shown - overpredict frequencies less than 10 Hz by as much as an order of magnitude, and should never be used for ENA.) However the scaled PGA-PGV spectra overpredict WNA motions for M5 earthquakes, and for large distances. ENA motions are overpredicted for M5 at frequencies less than 2 Hz, and M7 at intermediate frequencies. In many cases the error is greater than 100%. The implications for hazard analysis are discussed in the next section.

DEVELOPMENT OF SPECTRA FOR A SPECIFIED PROBABILITY LEVEL

Seismic hazard analyses to develop response spectra for use in engineering analyses are usually geared to some target probability level. The degree of agreement between scaled spectra and UHS will depend on the magnitude and distance ranges that contribute most strongly to the hazard. This in turn depends on the region, level of seismicity, and probability level. In order to characterize the resulting effects, response spectra were developed by the Cornell-McGuire method for probabilities of 0.002 per annum (or 10% chance in 50 years) and 0.0001 p.a. (1% in 100 years), for six example cases (Atkinson, 1989). The cases represent areas of low seismicity (eg. Toronto), moderate seismicity (eg. Cornwall) and high seismicity (eg. Charlevoix) in both the ENA and WNA tectonic settings. The difference in results between the two regions arises solely from the different ground motion relations. Table 3 lists the differences between the scaled spectrum (eg. hazard analysis performed for PGA and PGV, then spectrum constructed by scaling) and the UHS (eg. hazard analysis performed directly for PSRV at several frequencies), for the moderate probability level used in building code maps. The scaled spectrum appears to be a good approximation to the expected PSRV values for active areas of WNA (although note its applicability if large subduction earthquakes are considered has not been addressed), and for areas of low to moderate seismicity in ENA. In many cases of interest (eg. regions of low to moderate seismicity in WNA, and regions of high seismicity in ENA), however, the scaled spectrum significantly overestimates the UHS. This is because the most significant contributions to hazard are due to earthquakes that have spectral shapes very different from those assumed by the scaled spectrum approach.

DISCUSSION

Elastic response spectra obtained through scaling standard shapes to PGA and PGV contain significant errors for many types of earthquakes. Errors are even larger if spectra are scaled based on PGA alone. It is concluded that the use of scaled spectra is in general ill-advised, especially since there are now practical, more direct methods to obtain response spectra. The UHS is the recommended method of correctly depicting linear response parameters.

For the purpose of preparing building code hazard maps, it is desirable to depict the amplitude and frequency content of expected earthquake motions in as simple a form as possible. From examination of the test cased described in this paper, it has been determined that the following two-parameter algorithm accurately depicts the elastic response spectra. For ease of reference the two parameters have been named 'dynamic acceleration', a_d, and 'dynamic velocity', v_d. The dynamic acceleration is defined as the maximum response acceleration (eg. PSRV * 2 * pi * freq), at a frequency of 10 Hz in ENA, or at 5 Hz in WNA. The dynamic velocity is simply the PSRV at a frequency of 1 Hz. A simple spectrum can be constructed on a log-log plot of pseudo-acceleration vs. frequency, as follows:

- Plot v_d*2*pi at f = 1 Hz.
- Plot a_d at f = 10 Hz (ENA) or f = 5 Hz (WNA).
- Draw a horizontal line (eg. constant acceleration) for all frequencies above a_d.
- Draw a straight line connecting a_d to v_d (extrapolate this line to obtain lower frequencies).

This new algorithm is as simple as the PGA-PGV scaled spectrum in that it is also a bilinear shape based on two parameters. However because the two parameters are directly tied to the response spectrum, it is subject to dramatically less error. For WNA, errors for M 5 to M 7 earthquakes, at distances of 10 to 100 km, are generally less than 20% for all frequencies in the range 0.5 to 10 Hz. For ENA, errors are less than 20% for M 5 to M 7, at distances of 10 to 100 km, for the frequency range 1 to 10 Hz; at lower frequencies errors are more significant, but less than those for the scaled spectrum approach. When the new algorithm is applied to hazard computations for the six example cases, it is found to be much more accurate than the scaled PGA-PGV approach for moderate probabilities, with typical errors of less than 20%. Thus a_d and v_d would form a simple basis for national seismic hazard maps that could be used in building code applications to construct elastic response spectra. Note that PGA, where required, could be estimated by dividing a_d by the approximate dynamic amplification, which is about a factor of two (Newmark and Hall, 1982).

The UHS has recently been endorsed by several bodies. In 1989 a workshop on future U.S. building codes, sponsored by the National Center for Earthquake Engineering, revealed a strong consensus that national hazard maps for building codes should now be based on spectral ordinates, rather than PGA and PGV (Whitman, 1989). The UHS has also been recognized by the EERI Committee on Seismic Risk (1990), and the U.S. National Research Council's Panel on Seismic Hazard Analysis (1988). The Canadian Council for Earthquake Engineering is currently considering the UHS as a basis for seismic parameter mapping for the 1995 edition of the National Building Code.

Linear response spectra based on the UHS approach are a major improvement over scaled spectra and, by definition, very useful in dynamic analyses for structures which are expected to remain elastic. For extreme loading conditions, economic design of most structural systems requires that limited inelastic deformation be permitted. Recent work (Cornell and Sewell, 1988; Turkstra et al, 1989; Atkinson et al., 1990) has shown that design spectra can be constructed based on damage potential of motions, rather than linear response parameters. Current research efforts are aimed at developing appropriate ground motion relations for damage-potential parameters (such as ductility demand, defined as the ratio of system displacement to displacement at yield) as a function of magnitude and distance. Once these relations are developed, they can be readily used in seismic hazard analyses (eg. replace Step 3 in the right hand side of Figure 1 with the definition of a nonlinear response parameter for several frequency values).

The potential utility of ground motion relations for nonlinear response parameters is very significant. A hazard analysis for nonlinear spectra could be provided in a building code map, based on the UHS approach. This information, in conjunction with the estimated ductility and damping for the structural system, would provide the required yield force, to be used by a designer in proportioning members. Thus the nonlinear spectral approach has the potential to provide seismological information in a format which is of direct use to designers.

In conclusion, seismic hazard mapping should now be based on uniform-hazard linear response spectra. In the future, an increased emphasis on nonlinear response spectra is expected.

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TABLE 1 - Steps to Obtain Response Spectra for a Specified Probability

SCALED PGA-PGV SPECTRUM	UNIFORM HAZARD SPECTRUM
1. Use tectonic information to subdivide region into source areas or faults.	Same
2. Calculate magnitude-recurrence statistics for each source.	Same
3. Define ground motion relations for PGA and PGV based on empirical and theoretical earthquake database.	Define ground motion relations for PSRV at several frequency values based on empirical and theoretical earthquake data.
4. Compute PGA and PGV for selected probability.	Compute PSRV at several frequency values for selected probability. This is the UHS.
5. Estimate spectral values based on scaling algorithm using PGA and PGV. This is the scaled spectrum.	Not required
6. Modify spectrum for local site conditions, if required.	Same

TABLE 2 - Percentage errors for Scaled Spectrum Approach: Specified magnitudes and distances

CASE	ENA 0.5 Hz	ENA 2 Hz	ENA 10 Hz	WNA 0.5 Hz	WNA 2 Hz	WNA 10 Hz
M5 R10	220			320	30	
R30	200			320	40	
R100	160			250	100	100
M6 R10	50			50		- 40
R30	50			40		
R100				30	40	100
M7 R10	40	70				- 25
R30	30	80			25	
R100		60			100	100

TABLE 3 - Percentage Errors for Scaled Spectrum Approach: Expected values for probability of 0.002 per annum

CASE	ENA 0.5 Hz	ENA 2 Hz	ENA 10 Hz	WNA 0.5 Hz	WNA 2 Hz	WNA 10 Hz
low				70	120	180
moderate	50			200	120	
high	50	60		50	30	

FIGURE 1 - Spectra at R = 20 km
M5 ENA, M6 WNA