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CHARACTERISTICS OF SEISMIC HAZARD IN STABLE CONTINENTAL REGIONS AND ACTIVE TECTONIC REGIONS: RELEVANCE FOR DEVELOPING SEISMIC DESIGN CRITERIA

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ABSTRACT

Seismic hazard characteristics in low-seismicity stable continental regions (SCRs) and high-seismicity active tectonic regions (ATRs) typically differ in the degree of definition of seismic sources and ground motion attenuation. Because specific locations of active faults are often not known in SCRs, it is difficult to apply deterministic approaches to ground motion estimation that depend on defining seismic source-to-site distances. Typically, there is more uncertainty in the characteristics of seismic sources and ground motion attenuation in SCRs. This leads to more uncertainty in seismic ground motion estimates in SCRs than in ATRs. For probability levels and return periods typically used in seismic design, ground motions exceeding design levels may increase slowly with increasing return period in ATRs because ground motions may be approaching those of maximum earthquakes. In contrast, ground motions in SCRs increase relatively rapidly with increasing return period beyond design levels. Both the higher uncertainty associated with ground motion estimates and the greater rate of ground motion increases with increasing return period in SCRs suggest that longer return periods could be considered for developing design ground motions in SCRs as compared to ATRs. Differences in ground motion attenuation characteristics, differences in the magnitude of earthquakes that contribute to probabilistic seismic hazard, and differences in site response effects due to the dependence of soil amplification on ground motion level also lead to differences in seismic ground motion development in SCRs and ATRs.

KEYWORDS

Low-seismicity regions; seismic hazard; earthquake ground motion; seismic design criteria.

INTRODUCTION

This paper focuses on how the characteristics of seismic hazard in stable continental regions (SCRs) and active tectonic regions (ATRs) can influence the development of seismic design criteria in these regions. The eastern United States (EUS) is used as an example of an SCR and the western United States as an example of an ATR. In the following section, differences in seismic hazard characteristics, including characteristics of seismic sources and ground motion attenuation, in SCRs and ATRs are briefly summarized. This is followed by a discussion of the implication of these differences to developing seismic ground motions for design.

CHARACTERISTICS OF SEISMIC SOURCES AND GROUND MOTION ATTENUATION IN ACTIVE TECTONIC REGIONS AND STABLE CONTINENTAL REGIONS

Seismic Source Characteristics

In highly active plate boundary regions such as California and some other parts of the WUS, most moderate-to-large-magnitude earthquakes occur on active faults that are well defined in terms of their locations, geometries, and types of faulting. Although earthquakes can and do occur on features without surface expression off the mapped fault lines, such as blind thrust faults, the seismic hazard is usually dominated by the mapped active faults. Because the spatial extent, geometry, and type of faulting of these faults are known or can be reasonably estimated, it is possible to assess the maximum sizes of earthquakes that can occur on these features with some degree of confidence. Furthermore, Quaternary geologic slip rate data and paleoseismic evidence for earthquakes are commonly available and can be used to supplement historical seismicity data to assess earthquake recurrence rates on individual faults. Because of relatively high rates of seismic activity, seismicity data as well as geodetic data are available to constrain fairly well regional earthquake recurrence rates and, in some cases, recurrence rates on individual faults.

In contrast to the relatively good definition of seismic sources in active plate boundary regions, seismic sources are generally poorly understood and poorly defined in stable continental regions. Active faults having surface expression are rare, and the specific locations and geometry of seismogenic features in the subsurface are generally not known. Consequently, the maximum sizes of earthquakes cannot be estimated on the basis of fault dimensions, and geologic slip rates and paleoseismic data are generally not available to estimate earthquake recurrence rates. Recurrence rates are generally estimated regionally only on the basis of seismicity data, and these estimates are less well constrained than in seismically active regions because of the lesser amount of data.

Ground Motion Attenuation Characteristics

Ground motion attenuation characteristics may also differ between active tectonic regions and stable continental regions. Rates of attenuation may be lower in SCRs than in ATRs because of the presence of less faulted, more coherent crustal rocks. In the eastern United (EUS), the presence of harder rocks leads to a pronounced increase in the content of high-frequency motions (frequencies higher than about 5 Hz) and somewhat lower amplitudes of longer-period motions. The ground motion attenuation characteristics are better defined and constrained in the WUS than in the EUS because of the more abundant recordings of ground motion from a seismically active region.

IMPLICATIONS TO SEISMIC GROUND MOTION ESTIMATION AND DESIGN CRITERIA DEVELOPMENT

In the following paragraphs, the implications of the differing characteristics of seismic hazard in ATRs and SCRs to developing design ground motions are briefly discussed with respect to deterministic ground motion estimation; probabilistic ground motion estimation; and site response effects.

Deterministic Estimation of Ground Motion for Design

In the deterministic approach to estimating design ground motion in an ATR, an earthquake of a certain magnitude is assumed to occur on an identified active fault at a certain distance from the project site. Typically, the earthquake is assumed to be the maximum earthquake capable of occurring on the fault and is assumed to occur at the closest distance of the fault from the site. The assumption of the earthquake occurring at the closest distance, while conservative, may not be unreasonable because maximum earthquakes typically rupture a substantial fraction of the fault area. A deterministic approach to ground motion estimation is relatively easier to implement in an ATR where active faults are identified than in an SCR where specific fault locations are unknown. In an SCR, large seismic source zones are often characterized that are considered to have a uniform maximum earthquake potential and a uniform frequency of earthquake occurrence per unit area. For sites located in source zones, there is not a completely rational procedure for selecting a distance to a seismic source that is needed for a deterministic ground motion determination. It has sometimes been assumed that the earthquake occurs at a random location within a circle of a certain radius from the site ("random earthquake" approach). A statistical estimate of ground motions at the site (e.g., median or median-plus-standard-deviation) can then be made using either attenuation relationships or by statistically analyzing ground motion data for earthquakes of a size approximately equal to the design magnitude and recorded on site conditions similar to those at the site of interest within a distance equal to the selected radius. Obviously, such a ground motion estimate is greatly affected by the assumed radius. A 25-km radius has often been assumed as defining a reasonable region for the occurrence of a near-source earthquakes, but there is not a completely rational way to select this distance. For earthquakes occurring in a seismic source zone removed from the site, it is often assumed that the earthquake occurs at the closest point of approach of the source zone to the site. This can be extremely conservative if the source zone is large and the rates of earthquake occurrence are low (as is usually the case). These difficulties in rationally implementing deterministic methods in SCRs suggest that a probabilistic approach is more appropriate for ground motion estimation in such regions.

In either deterministic or probabilistic ground motion estimations, it is important to utilize attenuation relationships that are appropriate for the region. Figure 1 illustrates typical differences in deterministic ground motion estimates for nearby moderate magnitude earthquakes in the WUS and EUS due to difference in ground motion attenuation characteristics in the two regions. This illustrates that it is inappropriate to use "standard" spectral shapes in developing design ground motions for the EUS. Such standard spectral shapes, such as those developed by Applied Technology Council (1978) and which have been adopted into building codes, e.g., United States Uniform Building Code, have been developed based on ground motion data from ATRs, principally from the WUS.

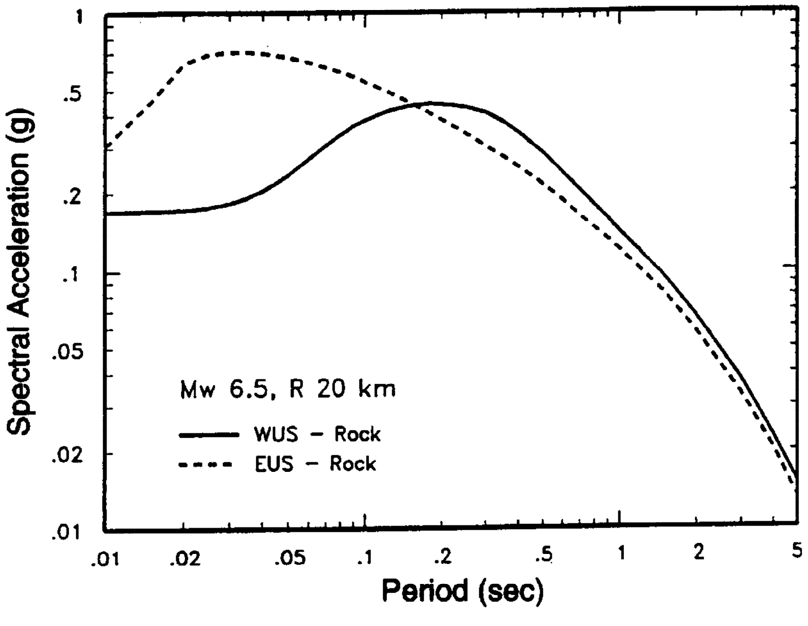

Fig. 1. Comparison of response spectra for a magnitude 6.5 earthquake at 20 km using WUS and EUS attenuation relationships (calculated using model as formulated by Silva and Green, 1989) (U.S. Army Corps of Engineers, 1995).

Probabilistic Estimation of Ground Motion for Design

In probabilistic ground motion analyses, the frequency of occurrence (recurrence) of earthquakes on seismic sources is combined with ground motion attenuation relationships in a probabilistic model to estimate ground motion levels as a function of their frequency or probability of exceedance. It is important to include in a probabilistic analysis the scientific uncertainties associated with seismic source definition and ground motion attenuation, such as uncertainties associated with the dimensions and segmentation of faults, locations and boundaries of seismic source zones, maximum earthquake magnitudes capable of occurring on seismic sources, earthquake recurrence rates on seismic sources, and appropriate ground motion attenuation relationships. Because seismic source characteristics and ground motion attenuation characteristics are less well defined in SCRs than in ATRs, there is greater uncertainty in probabilistic ground motion estimates in SCRs. An example is illustrated in Figure 2, in which seismic hazard curves for peak ground acceleration from probabilistic analyses are compared for sites in New York City and Portland, Oregon. As can be seen, the uncertainty in the hazard (measured from the 5th to the 95th percentile estimates of the hazard, i.e., 5th to 95th percentile confidence limits) is considerably greater for the New York City site. These types of results suggest that lower probability levels for design (or, correspondingly, longer design return periods) could be considered in SCRs to compensate for the additional uncertainties in probabilistic ground motion estimates in these regions as compared to more seismically active regions.

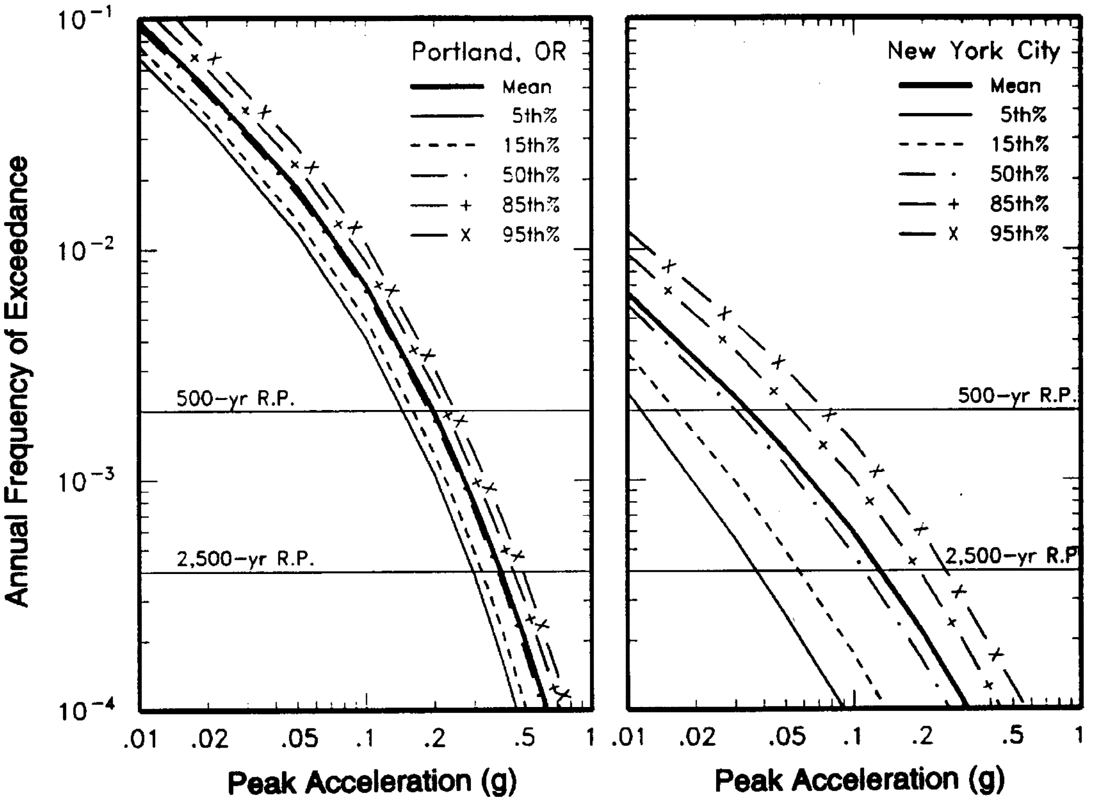

Fig. 2. Seismic hazard curves for peak ground acceleration on rock illustrating uncertainty in hazard estimates (Youngs, 1995).

Because of relatively low seismicity rates in SCRs as compared to ATRs, probabilistic estimates of ground motions at SCR sites at probability levels or return periods typically used in design (e.g., 10% probability of exceedance in 50 years, or 475-year return period) are farther from the ground motion levels associated with maximum earthquakes than those in ATRs. At such typical design return periods, ground motions in highly seismically active regions may be approaching or equal to those associated with maximum earthquakes, whereas in low seismicity regions, ground motions are much lower than those associated with extreme events. Figure 3 illustrates normalized peak ground acceleration mean hazard curves for sites in an SCR (New York City) and an ATR (San Francisco). The peak ground accelerations have been normalized to the values at an annual frequency of exceedance of 2 x 10^{-3} (i.e., 500-year period). It can be seen that for frequencies of exceedance lower than 2 x 10^{-3} (return periods longer than 500 years), the hazard increases much more rapidly for the New York City site than the San Francisco site. Although comparisons such as shown in Figure 3 depend on the specific site location and the particular ground motion parameter, the general trend is as shown in the figure and illustrates that ground motions a certain factor higher than the design level have a higher probability of being exceeded in low seismicity regions than in high seismicity regions. This implies a higher risk to a project in an SCR than an ACR where projects in both regions have been designed for ground motions having the same return period. Similar to the implications of greater uncertainty in SCRs as discussed previously, these results again suggest that longer return periods for design may be appropriate in SCRs than ATRs.

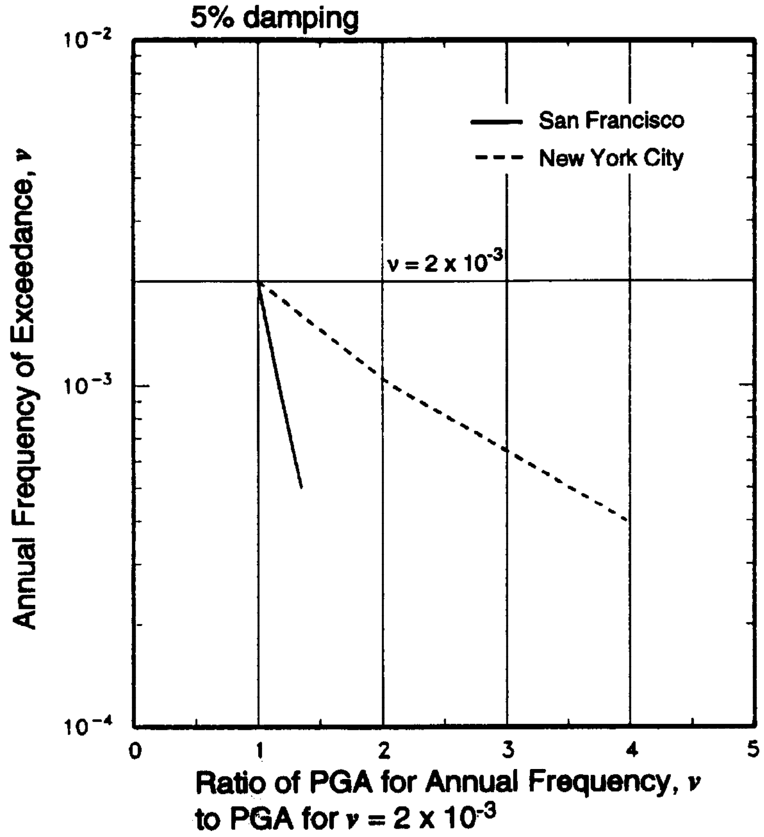

Fig. 3. Effects of annual frequency of exceedance on relative amplitudes of peak ground acceleration (PGA) for sites in EUS and WUS (Power *et al.*, 1995).

It is also typical in probabilistic ground motion analyses in SCRs (when sites are far from faults or seismic source zones having high seismicity rates and capability for large magnitude earthquakes) that the dominant contributors to seismic hazard are moderate magnitude, nearby earthquakes. In contrast, larger magnitude earthquakes often dominate seismic hazard in ATRs. These differences in earthquake magnitude contributions, combined with the differences in ground motion attenuation characteristics discussed earlier, can lead to substantial differences in response spectral shapes obtained from probabilistic analyses, a principal difference being a substantially lower content of long period motions at the SCR sites. This is illustrated in Figure 4 by a comparison of response spectral shapes obtained from probabilistic analyses for sites in San Francisco and New York City. The use of "standard" spectral shapes may greatly overestimate long-period ground motions in many parts of low seismicity regions.

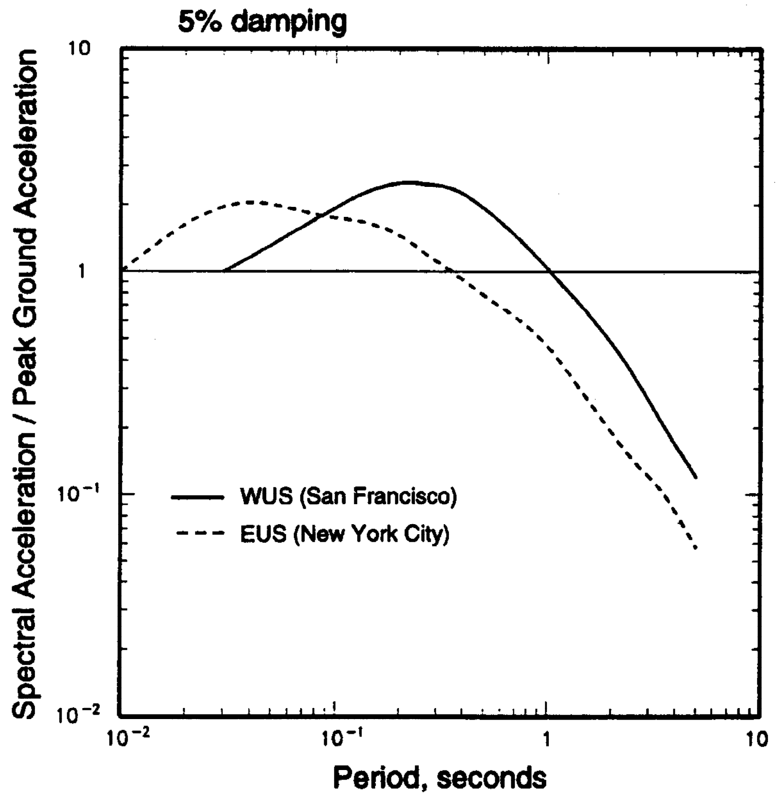

Fig. 4. Comparison of equal-hazard response spectral shapes for rock ground motions for a 500-year return period--sites in WUS and EUS (Power *et al.,* 1995).

Site Response Effects

In recent U.S. seismic design provisions (e.g., 1994 Uniform Building Code, ICBO, 1994; 1991 NEHRP Provisions, FEMA, 1992), site response (soil amplification) effects were incorporated for different soil profile types. These characterizations of site effects were region-independent.

The characterization of site response effects for seismic codes was reevaluated at a Site Response Workshop convened by the U.S. National Center for Earthquake Engineering Research, the Structural Engineers Association of California, and the Building Seismic Safety Council in 1992 (Rinne, 1994; Martin and Dobry, 1994). New site factors were recommended by the Workshop, which have been subsequently adopted into the 1994 NEHRP Provisions (FEMA, 1995) and also recommended by the Structural Engineers Association of California (SEAOC) for adoption in the 1997 Uniform Building Code. The new site factors (soil amplification factors) provide an improved generalized characterization of soil amplification effects for seismic design. In contrast to the "old" site factors, the new factors are a function of the levels of ground shaking; they increase for lower levels of shaking, reflecting less soil nonlinearity and lower soil damping for lower ground shaking levels. The new site factors principally affect site response effects on design ground motions in SCRs, where the higher factors (because of lower shaking levels in SCRs) result in higher soil amplification than those in ATRs.

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