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Empirical scaling relations for pseudo relative velocity spectra in western Himalaya and northeastern India

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ABSTRACT

In this paper, frequency-dependent empirical scaling equations are developed for pseudo relative velocity (*PSV*) spectrum amplitudes of strong earthquake ground accelerations in western Himalaya and northeastern India for five ratios of critical damping $\zeta = 0.00, 0.02, 0.05, 0.10$, and 0.20. These are based on the frequency-dependent attenuation functions developed in our recent work (Gupta and Trifunac [38]) for these two regions. The proposed scaling relations are shown to have physically realistic dependence on earthquake magnitude, source-to-site distance, and local site geological and soil conditions. The extension of the empirical *PSV* amplitudes to short and long periods, beyond the empirical period range, is also illustrated using available techniques (Trifunac [89,90]). To demonstrate the validity of a long-period extension, independent estimates of peak ground displacement from recorded accelerograms and estimates of the seismic moment from distant recordings of earthquakes are shown to be in good agreement with the extended spectral amplitudes. The validity of a short-period extension has been also tested by comparing the values of pseudo acceleration spectral amplitudes at short periods with the recorded peak ground accelerations. The realistic nature of short- and long-period extensions provides additional tests for the accuracy of the present scaling relationships. Such relationships can thus be considered to provide a sound basis for macro- and micro-zoning specific to the highly seismic regions of western Himalaya and northeastern India.

1. Introduction

The concept of response spectrum in earthquake engineering was introduced by Biot [9], who also proposed the first response spectrum superposition method [10] to obtain an upper bound on the response of multi-degree-of-freedom (MDOF) structures. Since then, a large number of response spectrum superposition rules have been proposed by different investigators in a bid to achieve closer matching with the exact maximum response of MDOF structures with varying complexities ([113,22,69,76,82–84;20,5,86]; etc.) Important later developments relate to generalizing the response spectrum superposition method in order to gain statistical estimates of several significant peaks of the response amplitudes corresponding to the strong-motion stationary part of input ground excitation [30–35,37,39,4,40,41]. Presently, response spectrum methods are used extensively in earthquake-resistant design applications to characterize the design ground motion in terms of the response spectrum. Empirical scaling equations regarding all of the significant governing parameters, which can be assigned easily and accurately, are the most common method for describing the response spectrum amplitudes.

Trifunac [89] developed empirical scaling relations directly for Fourier spectrum (*FS*) amplitudes at different periods in terms of earthquake magnitude, epicentral distance, site geological condition, and component of motion. The same was then extended to the amplitudes of various types of response spectrum [101–103,91]. The site geology in these studies was defined qualitatively by a parameter s taking values of 0, 1, and 2 for sites on sediments, intermediate sites and geological basement rock sites, respectively. This was later refined to the depth h in km of the sedimentary deposits beneath the recoding station [105,106]. The attenuation with distance in all of these studies was defined by Richter's [75] attenuation function $A_0(R)$. In subsequent studies for attenuation of *FS* amplitudes [109,111], as well as the pseudo relative velocity (*PSV*) spectrum amplitudes [110,112], this was replaced by an improved frequency-dependent attenuation function $Att(\Delta, M, T)$ defined in terms of an equivalent source-to-site distance Δ, earthquake magnitude M, and the wave period T [107,108]. The next development [49–51,92–94] was to introduce the dependence on the site soil condition as defined qualitatively by a parameter s_L

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taking on values of 0, 1, and 2 for sites on rock soil, stiff soil, and deep soil, respectively. Trifunac [95] has shown that the strong ground motion amplitudes depend significantly on both the local geological and site soil conditions. Yet another development was to define the effect of inhomogeneities along the propagation path by introducing the dependence of rock percentage along the source-to-site path in the empirical scaling relations [58,59].

Although all of the foregoing developments were specific to Southern California, they have also been applied to other parts of the world. Lee and Trifunac [56] developed the frequency-dependent attenuation function $Att(\Delta, M, T)$ for the former Yugoslavia and used it to generate empirical scaling relations for *FS* [57] and *PSV* [52] amplitudes. The scaling relations for the former Yugoslavia have been modified by developing an independent frequency-dependent attenuation function to describe the scaling of *FS* [63] and *PSV* [64] amplitudes from the deep focus and distant Vrancea earthquakes in Serbia. Gupta and Trifunac [38] have recently developed frequency-dependent attenuation functions and scaling relations for Fourier spectrum amplitudes for western Himalaya and northeastern India, which have been extended to the *PSV* amplitudes in the present work. The same functional form and regression method used for the *FS* amplitudes has also been adopted for the scaling of *PSV* amplitudes in this work, using the same database of 1236 components of accelerograms recorded in both regions of India.

Starting with the work of Johnson [44], a large number of scaling equations have been developed for the response spectrum amplitudes at different periods for various seismic regions around the world [21]; however, no worthwhile relationship is available for any part of India. A limited number of strong-motion data became available in India during the period of 1986–1999 from three isolated networks of about 40–50 analog accelerographs each—two operated in western Himalaya and one in the Shillong Plateau area of northeastern India [13]. This database formed the basis for a few models of ground motion peaks (e.g.; [14,72,79,85]). The first model for the scaling of *PSV* amplitudes was developed for northeast India by Das et al. [17] and used for the macrozonation of the region. However, due to the very limited database available, the authors combined the data from both shallow crustal and deep subduction earthquakes and could not include the dependence on site geological and soil conditions. Using 56 three-component accelerograms, Gupta [28] modified the attenuation relationship of Atkinson and Boore [8] to suit the ground motion amplitudes in northeastern India caused by Burmese subduction-zone earthquakes. This relationship showed a slower attenuation of pseudo spectral acceleration (*PSA*) amplitudes than the previous model of Das et al. [17]. Sharma et al. [80] proposed a scaling model for *PSA* amplitudes for the Himalayan region by using a larger database obtained by combining the data from the Zagros region in Iran. However, the similarity of the strong ground motion characteristics in the Himalaya and Zagros regions could not be justified. In addition, they considered only “rock” and “other” types of site conditions, which does not adequately describe the site effects.

In light of the previous discussion, most of the recent seismic hazard studies in India [18,47,7,70,71,77] have used arbitrarily selected ground motion prediction equations from other regions of the world rather than the available India-specific attenuation relationships. None of these studies performed any checks on the ability of the selected attenuation relations to describe the strong ground motion amplitudes in the area of interest in India. The reliability of such studies is thus questionable and difficult to assess. The scaling relations for *PSV* amplitudes proposed in this study for damping ratios $\varsigma = 0.00, 0.02, 0.05, 0.10$, and 0.20 will provide an improved basis to obtain a more reliable seismic hazard assessment specific to vast areas of western Himalaya and northeast India. The magnitude used in the present relations is the published magnitude, which can be defined directly without any requirement for empirical conversion into a specific magnitude type. In a hazard analysis, magnitude conversion is commonly a source of large uncertainties that are unaccounted for. Also, as discussed in our paper on Fourier spectra scaling [38], the use of moment magnitude is not appropriate for the scaling of high-frequency, strong-motion amplitudes between about 0.1 and 25 Hz. The distance used in our present scaling model is primarily the hypocentral distance, an estimation that does not involve the uncertainties usually associated with the estimation of fault-rupture distances, such as the closest distance to the fault- rupture plane or the surface projection of the rupture plane [24]. Further, the simple qualitative parameters used to define the site geological and soil conditions in the present scaling equations can capture the site amplification effects in a physically realistic manner, and it would be much easier to define these in practical applications.

Typical examples of the *PSV* spectra estimated from the proposed relations have illustrated that such spectra can account for the dependence on magnitude, distance, and recording site condition in a physically realistic and accurate way. The rate of growth of *PSV* amplitudes with magnitude is seen to slow down with an increase in magnitude, thus reaching a maximum beyond a certain magnitude that is larger for larger natural periods. Thus, the magnitude dependence is constrained in a very realistic manner. Also, the increase in spectral amplitudes is seen to slow down with a decrease in distance, which is the desired distance-saturation effect. Similar to the *FS* amplitudes [38], the *PSV* amplitudes are also seen to be larger on sediments compared to the basement rock at periods longer than about 0.24 s for all types of site soil conditions. However, unlike the *FS* amplitudes, the *PSV* amplitudes are larger on the stiff, as well as soft soil sites compared to rock soil in all periods. The *FS* amplitudes are seen to be higher on rock soil for periods below about 0.1 s. This can be considered as realistic behavior, because the high-frequency response spectral amplitudes also have significant contributions from lower frequencies. However, the amplification on soft soil sites is not seen to be that large at periods below 0.1 s. Finally, very good agreement will be shown to exist between the estimated and the actual response spectra of the recorded accelerograms.

To minimize the effects of the low- and high-frequency noise invariably present in the recorded strong-motion acceleration data, the proposed empirical relations for both western Himalaya and northestern India are presented for the period range of $0.04\ -3.0$ s only. However, for the design of long structures, tall buildings, and structures on multiple distant supports, it becomes necessary to specify the design ground motion for much longer periods. Also, the design of equipment and stiff structures requires specifying the design ground motion at higher frequencies (short periods). The methods proposed by Trifunac [97,98] based on simple theoretical considerations is used in this work to show how the *PSV* spectral amplitudes can be extended to both long and short periods beyond the range within which the empirical scaling relations apply. The validity of such extrapolations for northeast India and western Himalaya has been tested and validated by comparing the estimates of seismic moment, peak ground displacement, and peak ground acceleration with other independent estimates of these quantities.

2. Strong-motion database used

The strong-motion database used for developing the empirical scaling relations for PSV amplitudes in this study is the same as detailed in Gupta and Trifunac [38] for developing similar relations for Fourier spectrum amplitudes. This includes 412 three-component accelerograms from 113 different earthquakes, from which 252 records are from 72 earthquakes in western Himalaya and 160 records from 41 earthquakes in northeastern India. Older analog, as well as later digital types of records, are considered in the database. Our database comprises 90 analog records (35 in western Himalaya and 55 in northeatern India) and 322 digital records (217 in western Himalaya and 105 in northeatern India). Analog data is recorded by 3 localized networks of 40–50 accelerographs operated by IIT Roorkee during the 1986–1999 period in the Kangra and Garhwal-Kumaon areas of western Himalaya