Soil Dynamics and Earthquake Engineering 102 (2017) 137–159

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Scaling of Fourier Spectra of strong earthquake ground motion in western Himalaya and northeastern India

I.D. Gupta[a], M.D. Trifunac[b,*]

[a] Department of Earthquake Engineering, IIT Roorkee, Roorkee 247667, India
[b] Dept. of Civil Engineering, Univ. of Southern California, Los Angeles, CA 90089, United States

ARTICLE INFO

Keywords:
Strong motion attenuation models
Fourier spectrum amplitudes
Western Himalaya
Northeast Indian region
Regression analysis
Seismic hazard

ABSTRACT

It is necessary to develop scaling models of various functionals of ground motions for different seismic regions to obtain region-specific motion characterizations for the design of structures and for seismic hazard studies. Until recently, a paucity of strong-motion data has limited such work in seismic regions in India. In this study, scaling of Fourier spectrum amplitudes is attempted for the western Himalayan and northeast regions of India in terms of magnitude, source-to-station distance, component orientation, and geological and soil site conditions. The scaling model considered is similar to that of Trifunac and co-workers for the California region in the 1980s and 1990s. A database of 1236 recorded accelerograms for both regions of India is used with the assumption that dependence on earthquake magnitude, site geology, site soil and component direction is the same. Separate attenuation models are then developed for the western Himalayan and northeast Indian regions in the period range of 0.03–3.0 s. The assumption of identical dependence of Fourier amplitudes on earthquake magnitude in the western Himalaya and northeast India region is found to be consistent with the actual data. These amplitudes grow with magnitude, reaching a maximum for magnitude around 7.0 for periods below 0.1 s and for magnitude exceeding 8.0 for longer periods. The Fourier amplitudes are amplified on sediments (with respect to basement rocks) at periods longer than 0.24 s, which are also amplified on "stiff soil" (with respect to the "rock" soil sites) at periods longer than 0.2 s. Extension of the proposed models to shorter and longer periods is also presented using the available techniques and validated by establishing their consistency with the independent estimates of seismic moment, stress drop, and radiated wave energy in both western Himalaya and northeast India.

1. Introduction

India has been home to some of the most devastating earthquakes in the world. Both the northwest and northeast parts of the country form part of the Himalayan plate boundary, which has experienced some of the largest earthquakes recorded in recent history. These earthquakes have caused great loss of life and property. Thus, it is desirable to have reliable estimates of future ground motions for seismic risk reduction in these areas and to design earthquake-resistant structures. This can be done provided the anticipated ground motions are characterized suitably with knowledge of the seismicity of the region under consideration and strong ground motions recorded during past earthquakes.

The methods used for the characterization of (anticipated) ground motions typically require the development of ground motion prediction equations (GMPEs) or scaling models for the region. These equations give a measure of the intensity of strong ground motion in the form of the peaks (such as peak ground acceleration (PGA), and peak ground velocity (PGV)), spectral amplitudes (such as pseudo spectral velocity (PSV), pseudo spectral acceleration (PSA), and Fourier spectrum (FS) amplitudes), or other functionals (such as strong-motion duration) of the ground motions. The input parameters used in these equations are earthquake magnitude, source-to-site distance, soil conditions, and other governing parameters, and depend on the rigor (with the introduction of more governing parameters) with which these equations are designed. A large number of such scaling equations have been developed in the past for various seismic regions of the world from their strong-motion records, most of which have been developed for ground motion peaks, particularly PGAs (e.g.; [10,28,30,36,44,82]). However, since the ground motion peaks correctly convey information in only a limited range of frequencies (e.g., PGA correlates well with the energy in the frequencies greater than 10 Hz), using these parameters alone for synthesizing the entire response spectrum can result in large deviations from the actual spectral amplitudes in the rest of the frequency bands [87]. It is for this reason that the spectral amplitudes of ground motions are directly scaled from the strong-motion records (e.g., [1,3–5,12–14,45,55,56,83,84,94,97,98]). An up-to-date compilation of

* Corresponding author.
E-mail address: trifunac@usc.edu (M.D. Trifunac).

http://dx.doi.org/10.1016/j.soildyn.2017.08.010
Received 13 July 2017; Accepted 20 August 2017

such relations is given in Douglas [27]. The equations proposed in this study describe the spectral amplitudes in terms of magnitude, distance, and site conditions.

Moment magnitude has been used by most researchers to represent earthquake magnitudes. However, Gupta [33] argued that moment magnitude cannot be considered appropriate to scale the strong-motion amplitudes between, 0.1 and 25 Hz. This is because moment magnitude is a measure of the spectral amplitude at zero frequency and its use for frequencies above 0.1 Hz assumes that the spectral amplitudes variations between 0 and 0.1 Hz are known, which, of course, is not the case. Trifunac [83], Trifunac and Lee [97,98], and Lee and Trifunac [55,56] have used local magnitude for scaling the spectral amplitudes of small earthquakes (with magnitudes less than 6.5) and surface-wave magnitude for larger events.

Different researchers have used a variety of means to quantify the site effects on the amplitudes of ground motions. Joyner and Boore [44,45] used a simple classification and categorized their data as rock or soil. Boore et al. [12], Ambraseys et al. [3–5] categorized their data based on the average shear wave velocity in the top 30 m of soil and used a categorical variable to distinguish between different sites in their scaling equations. Boore et al. [13,14] preferred to directly use the average shear wave velocity (in the top 30 m of soil). In early work, Trifunac [82,83] considered only geological site classification, but in Trifunac [84], he argued that both geological and soil conditions should be used, as different depths corresponding to these two classifications affect different frequencies of waves, and ignoring the geological conditions will give exaggerated results for the soil conditions. Lee and Trifunac [55,56] considered both geological and soil conditions in their scaling equations, and assumed the soil classification to be based on the definition proposed by Seed et al. [72].

Another notable difference in the scaling models proposed by different researchers is related to the way distance parameter is defined to model attenuation. Boore et al. [12–14] considered hypocentral distance such that the depth parameter is determined from the regression analysis. Boore et al. [12] considered separate regression coefficients for the hypocentral distance and its logarithm, while Boore et al. [13,14] used a regression coefficient only for the logarithm of hypocentral distance. Abrahamson and Silva [1] used a term similar to hypocentral distance, such that the closest distance to the fault rupture is taken as the epicentral distance. Trifunac and Lee [96,97] considered a representative distance proposed by Gusev [35] as a function of epicentral distance, focal depth, earthquake size, and sub-source radius. Since the sub-source radius is defined as a function of the incoming waves' wavelength [35], the representative distance became frequency-dependent, and as the size of an earthquake depends upon its magnitude, it also became magnitude-dependent. Lee [51] argued that since a source has finite dimensions, and high-frequency waves attenuate faster than low-frequency waves, the attenuation term should be both magnitude- and frequency-dependent.

In many studies (e.g.; [1,4,5]), separate equations have been developed for the horizontal and vertical components of ground motions. However, Trifunac [83] and Trifunac and Lee [96,97] proposed the same equation for both horizontal and vertical motions by recognizing that two components of any motion should have an identical dependence on parameters such as magnitude, distance, and site conditions. The authors introduced a parameter for the component orientation (equal to 0 for horizontal and 1 for vertical components), and the ratio between the spectra for the two components is then obtained in the form of a (period-dependent) regression coefficient.

Any scaling model developed from the recorded strong-motion data has inherent limitations that depend on the strong-motion accelerographs used to record the data, as well as the frequency range in which the data can be considered reliable. Trifunac [88–90] recognized this and, by using available seismological models, showed how the frequency range of any scaling model could be extended to shorter and longer periods.

In India, the inception of the "Indian National Strong Motion Instrumentation Programme" [19] and the availability of strong-motion data in the 1980s and 1990s led to the development of a few models of ground motion peaks based on a small database for the Himalayan region (e.g.; [20,63,74,78]). Chandrasekaran [20], Singh et al. [78], and Sharma [74] used a model that considered only magnitude and hypocentral distance and ignored the role of site effects. Parvez et al. [63] further developed separate attenuation equations for the eastern and western Himalayas. They addressed the problems related to the lack of data by using the theoretical distance attenuation model proposed by Gusev [35] and the empirical magnitude dependence proposed by Fukushima and Tanaka [30].

Das et al. [25] developed a scaling model for PSV spectrum for northeast India by considering the hypocentral distance as the distance parameter. They considered both horizontal and vertical components in the scaling model but ignored the geological and soil effects at the site. Sharma et al. [76] proposed a model to scale PSA spectrum for the Himalayan region. They considered a larger database by including the data from Iran's Zagros region under the assumption that the seismotectonic settings were similar to that of the Himalayan region. In addition, they considered only the horizontal component of ground motions and categorized their data into "rock" and "other" sites.

There has been a rapid increase in the database of recorded strong motions in the Himalayan region since the establishment of the "National Strong Motion Instrumentation Network" in 2005 by the Indian government. Although this database is still not large enough to provide a balanced distribution with respect to earthquake magnitudes in different seismic regions of India—or for developing a comprehensive attenuation model for each of these regions—it may be sufficient to provide some preliminary trends of the spectral amplitudes in the western Himalayan and northeast Indian regions.

In the present work, scaling models are developed by means of regression analyses to predict Fourier spectra for the western Himalayan and northeast region of India. The parameters considered for these models are earthquake magnitude, source-to-site distance, geological and soil conditions at the site, and component orientation. The functional form considered is similar to that proposed by Trifunac [84]. Scaling models are developed for the Fourier spectrum based on their usefulness in characterizing the frequency content of the ground motion and in obtaining the response spectrum amplitudes [102,16,40]. Also, it will be shown that the empirical prediction models developed in this study can be extended to longer and shorter periods using the methodology proposed by Trifunac [88–90]. To show that such extensions provide physically realistic results, estimates of seismic moment, effective stress drop, and radiated seismic wave energy will be shown to be in good agreement with other independent seismological estimates.

2. Earthquakes, recording stations, and strong-motion database

2.1. Strong-motion database and contributing earthquakes

The regions of western Himalaya and northeast India selected for the present study are among the most seismically active areas in the world; however, the strong-motion data available for these regions has been, until recently, inadequate. In spite of an early start of a strong-motion instrumentation program developed and deployed by the indigenous RESA (Roorkee Earthquake School Accelerograph) series of accelerographs in Himalaya by the Department of Earthquake Engineering (DEQ) at the University of Roorkee (currently known as the Indian Institute of Technology (IIT), Roorkee) in India in the 1970s, no strong motion data is known to have been recorded. The first database of 147 three component records from 13 different earthquakes have recently become available for the 1986–1999 period [23,77]. These records came from 135 state-of-the-art analog accelerographs (the SMA-1 manufactured by Kinemetrics) that operated in three localized networks, with 40–50 instruments each in the Kangra and Garhwal-