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Attenuation of strong earthquake ground motion – I: Dependence on geology along the wave path from the Hindu Kush subduction to Western Himalaya

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ABSTRACT

The common approach to describing the attenuation of strong earthquake ground motion has been in terms of a variable that measures the length of the wave path between the earthquake source and the recording site. Although in some published empirical scaling equations, soil and geological conditions at the recording site also have been included via simple site-specific parameters, however, with few exceptions, the geology along the wave propagation path has been generally ignored. This has resulted in excessive residuals of predicted amplitudes and increases the uncertainty in the end results—namely, prediction of design amplitudes for earthquake-resistant structure design. In this paper, we describe one example in which the dependence of attenuation equations on the geology can be demonstrated due to a clear separation in the location of contributing earthquake sources and the associated differences in the geological environment along the wave paths. Our example shows the advantages of including a geologic description along the path of seismic waves and thus design amplitude predictions can be developed more realistically and with certainty for a given region.

1. Introduction

After the first strong motion acceleration was recorded in 1933 (March 10, 1933, Long Beach, California, earthquake; [82], it then took more than four more decades to record a sufficient number of accelerograms to enable the first regression analyses of the observed amplitudes. Early attempts to relate peak acceleration of strong motion with earthquake magnitude and distance can be found in papers by Gutenberg and Richter [28,29] and Neumann [55]. By the mid-1960s, although other papers began to appear for scaling in terms of magnitude, distance, and site intensity, there were no references to geology at the recording site or along the wave propagation path. The equations used to describe strong motion amplitudes had simple mathematical expressions that were suitable for linear regression analyses but ignored the physical nature of the problem and in particular its dependence on the medium along the wave path.

In subsequent years, earthquake engineering methods for the estimation of applied ground motion for design converged towards the scaling of design spectra in terms of peak ground acceleration. Numerous empirical equations were published describing peak acceleration in terms of earthquake parameters and earthquake-to-site distance [18]. The majority of these equations ignored the influence of geology along the wave path and at the recording site. Papers on seismic microzonation (e.g., [43,49-51,76], however, have shown that local geological site conditions play a significant role in determining the expected strong motion amplitudes and should not be ignored. In light of this, it is remarkable how many studies have still continued to develop scaling equations using only the soil-site classification variables (e.g., [1,3–5,10–12], as though all strong motion data has been recorded under identical geologic site conditions.

The first attenuation equation for peaks of strong motion amplitudes that used regionally calibrated attenuation for average geologic conditions in southern California [88] was based on the attenuation equation adopted by Richer for calculation of the local magnitude scale [62]. Because the seismicity in southern California is mainly confined to the top 20 km of the Earth's crust, Richter's attenuation is suitable for waves with relatively shallow paths and with wave energy centered near 1 s periods, which also coincides with the frequency range of recorded strong ground motion in the same region.

With a gradual increase in the number of recorded accelerograms, more detailed empirical scaling equations were developed through the 1980s and 1990s. Frequency dependent attenuation was introduced in 1985 [89,94], and the simultaneous dependence of recorded amplitudes on soil-site and site-geological parameters in 1987 [73]. However, in most other scaling equations that pertained to California published during 1980s and 1990s, geologic characteristics along the wave

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path between the source and the station, as well as the local geological site conditions at the recording station, were not included.

The first work to consider geological effects along wave paths in California assigned a path type for each earthquake and a recording station pair depending on the number of sedimentary basins traversed along the way. A parameter representing the percentage of length fraction traveling through basement rocks was used in regressions and shown to be significant [53]. This analysis considered geology in the simplest “binary” fashion either as basement rocks or as sediments. No attempt was made to group the paths in terms of more detailed geological descriptions, age, and geometry and composition of sedimentary basins, nor in terms of the differences in sampling the deeper geology for waves that traveled from greater distances. The study by Lee et al. [53] was made possible by maps of sedimentary basins that are fairly detailed and complete, thanks to the oil exploration work in southern California [68].

Realization that the waves from deep earthquakes in the subduction zones propagate along deeper wave paths than earthquakes from shallow events in the crust has led to the studies of attenuation functions tailored specifically for such events (e.g., [7,101]). However, different subduction zones have different geometrical and geological characteristics so that collectively analyzing recorded motions from several such zones cannot produce reliable attenuation equations for each subduction zone separately [19,23]. Our first study, which showed the effects on attenuation functions caused by sampling deeper geology along the source-to-station paths, was carried out for Vrancea earthquakes (with hypocenters 80–135 km deep) in Romania [48]. This study showed slower attenuation with distance for wave paths through deeper and faster rocks, compared with the attenuation for shallower earthquakes in the same region [44,45]. The nature of these differences, which depend on the variations in the velocity structure in the rocks along the wave path, as well as on their Q factors [78] at depths, is analogous to what will be described in this paper.

Comprehensive description of the effects of geological factors that influence the nature of attenuation equations along the wave propagation path is a challenging problem. Such an analysis requires detailed three-dimensional maps of wave speeds along the wave path and a large number of recorded data from dense networks. Because such maps are not available, and the data from dense instrument arrays is rarely available, only several simple analyses for one earthquake source volume at a time and different paths have been attempted thus far (e.g., [58,69,70,95,96].

Careful calibration of the region, wave paths, and source-dependent attenuation functions are essential for mapping seismic hazard in terms of the Uniform Hazard Spectrum Method (UHSM) [46,47,49,50,51]. This method makes it possible to include, in a balanced way, contributions to hazards from moderately near and large, distant earthquakes and from earthquake waves experiencing different attenuations along their paths. However, this method also requires that different scaling and attenuation equations must be available a priori for each contributing earthquake source zone. In this paper we contribute toward such scaling and attenuation equations for Fourier and pseudo-relative velocity (PSV) spectra from Hindu Kush earthquakes recorded in Western Himalaya in India.

2. Hindu Kush source zone

The Hindu Kush source zone, which contributed recorded accelerations in Western Himalaya for this study, is located near the northern end of the orogenic belt between India and Tibet. Fig. 1 shows the areas surrounding the collision zone of the Indian subcontinent with Asia, one of the important geological events in the last 100 Ma [99]. This collision produced the Tibetan Plateau, with an average elevation of 5000 m. This plateau is the source of the river systems (Yellow, Yangtze, Red River, Salween, Irawaddy, Brahmaputra, Ganges, Indus, Amu Darya, and Syr Darya), which served as incubators for human civilization in Southeast Asia, India, and Persia.

The manner in which the Tibetan Plateau evolved and the spatial and temporal (Eocene and Pliocene) interpretation of the models aiming to explain the collision with the Indian subcontinent continue to be the subject of lively debate [2,100]. From an earthquake engineering viewpoint, the subject is of considerable interest, because the orogenic belt between India and Tibet (Fig. 1a) is the source of some of the largest earthquakes in the world that occur in high-denstiy population areas and constitute a hazard that needs to be quantified and mitigated. The Hindu Kush seismic source region alone has produced 15 large earthquakes ($M_w > 7$) in the last 100 years [37], and the shaking from these events will produce significant contributions to the long period UHS amplitudes in northwest India.

Seismic data from a 40-station array in southern Kyrgystan and eastern Tajikistan that operated from mid-2008 to mid-2010 provided data used by Sippl et al. [67] to infer the geometrical relation between the Pamir and Hindu Kush earthquake zones. Their data shows Pamir, located northeast from the Hindu Kush, as an arc that incrementally changes its dip from southward to eastward and its strike direction from east-west to north-south from east to west. Southwest from the Pamir Arc, separated from by a dip in direction, is the Hindu Kush slab, which strikes east-west and dips almost vertically toward the north (Fig. 2). Smaller in width, the Hindu Kush is more complex than Pamir and seismic data suggests its slab breaks off into several fragments.

The Hindu Kush earthquake source volume is associated with a low attenuation of seismic waves, which is common for the Benioff zones beneath island arcs. Studies of the Pamir-Hindu Kush seismic zone also suggest that the prominent zone of intermediate-depth seismicity occurs along thin (< 30 km) and deep slab-like zones similar to oceanic subduction zones [16]. This implies a subduction of a small, trapped oceanic basin. However, the geology of the Pamir, Hindu Kush, and Tadjik Basin regions demonstrates that no oceanic crust has existed in the region (including the Pamir, Hindu Kush, Karakoram, and Western Tibet) since at least the Mid- to Late Cretaceous periods [65]. The youngest marine sediments along the Indus suture zone and north Indian plate margin (Himalaya) are from the earliest Eocene (54–50 Ma). Several authors have suggested that the seismic zone represents a subduction of thinned continental crust, with a north-dipping Hindu Kush seismic zone, and earthquakes at depths of 90–280 km. The Pamir and the Hindu Kush are both relatively old (Jurassic-Cretaceous) mountain ranges that have been uplifted and reactivated during the Neogene continental collision of India. Although the Asia-India collision has been taking place since ~50–55 Ma (van Hinsbergen et al., [97], the current convergence rate is still high, at ~34 mm/year in this area. [17].

Fig. 3 shows the Hindu Kush earthquakes and the accelerograph stations in the Western Himalaya that recorded those events (shown by filled triangles). The hollow circles are shallow crustal earthquakes contributing data at all sites (shown by triangles) in the study by Gupta and Trifunac [25]. The accelerograph sites that recorded data from subduction earthquakes are mostly located on thick sediments and/or deep soil sites. The bottom of Fig. 3 clearly shows that the waves from the Hindu Kush zone will travel along deeper paths compared to the shallow earthquakes in Western Himalaya and thus sample different and much deeper geologic materials. This sample will then result in different attenuation functions from the one we described in Western Himalaya. Our results will describe the average attenuation for waves from the group of earthquakes that we analyze. These attenuation equations will naturally vary with changes in the source depth and source mechanism.

Our analysis describes the attenuation of spectra of strong ground motion from Hindu Kush earthquakes in the southeast direction ($127° < \varphi < 138°$). It is anticipated that this will allow us to assume that the results from the current paper may approximate the attenuation from Hindu Kush earthquakes towards New Delhi (φ~145°) for calculations of seismic hazard in future papers.