Impact of directional effect of strong ground motion on scenario-based earthquake hazards: preliminary results

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Abstract. Scenario-based earthquake hazards are useful for social planning and disaster mitigation. In this study, general attenuation properties of earthquake events are analysed empirically with respect to the direction of seismic rupture from the epicentre. The study is primarily focused on presenting a relationship between fault source characteristics and the most credible direction of any earthquake that occurs at that source. Since such a direction is not only a function of source but also is dependent on site parameters, several ground motion prediction equations are utilised in congregation with methods to evaluate site parameters. The method involves a graphical relationship between scenario spectral ordinates and polar coordinates to estimate the most credible direction for that scenario. An analysis illustrating the method is presented here for the Himalayan megathrust fault, the Main Boundary Thrust.

1. Introduction
Earthquakes are one of the most prominent natural hazards that cause countless destruction to life and property both socially and economically. They often pose a high-level threat to all kinds of civil structures be it buildings, bridges, or dams. The impact of destruction is not confined at the vicinity of the source but goes as far as 300-400 km (Villaverde 2009). To reduce earthquake losses due to ground failure, several methods have been proposed to understand earthquake dynamics and their perspective location, date and time, intensity, and nature of devastation. In this direction, seismic hazard analysis, a term associated with the selection of ground motion characteristics based on historical information, geological data, statistical inferences, and empirical correlations, is often carried out. It involves both deterministic and probabilistic hazard analysis including scenario-based earthquakes, and provides information of conditional probability of earthquakes (exceedance probability curves), interevent time analysis, peak ground accelerations (PGA), and peak ground velocities (PGV) at the target areas (Villaverde 2009). The basic inputs are the types of geological faults and seismic sources, recurrence patterns, medium characteristics, and the attenuation relationships to estimate the ground motion for a given source-to-site distance and size of the seismic event. In this regard, most credible direction (MCD) is defined as the direction where PGA or spectral ordinates’ amplitudes attenuate with the slowest rate as compared to other directions of attenuation. The concept of MCD not only is useful to identify high risk areas but also is important for structural engineers to effectively design seismic-resistant structures. In a recent study on the effect of ground motion direction on the response of engineering structures (Sun et al. 2016), the authors have used various statistical techniques and coordinate transformations to demonstrate that peak and phase of the ground motions are quite different in different angles. Similarly, during the 2013 Lushan earthquake in China, it was observed that the difference in structural internal force between the maximum ground
motion direction input and the input of original seismic record is immense (Nie et al. 2018). Therefore, response spectrum analysis of various hypothetical (scenario-based) earthquakes in the vicinity of large-scale structures of national importance such as Taj Mahal, Qutub Minar, Fatehpur Sikri, and Red Fort could be of major help in improving the structural strength of monuments by identifying the most credible directions of perspective earthquakes originated in and around the active Himalayan seismic belt.

In view of the above, the present study provides a relationship between fault source characteristics and the MCD of scenario-based earthquakes. We compare various source dependent parameters such as fault type, fault orientation, direction of rupture, depth of rupture, magnitude of earthquake, and site dependent propagation medium characteristics to find out appropriate attenuation equations applicable to the model, usually representable with the help of spectral ordinates such as spectral acceleration, spectral velocity, PGA, and PGV. We thereafter formulate equations to evaluate associated parameters for site including different kinds of distances and fitting them with $V_{S30}$ (the mean velocity of shear wave to a depth of 30 m) profiles. Finally, we utilise attenuation equations and the corresponding regression coefficient tables to construct hypothetical earthquake scenario for the study site and use them to evaluate the MCD for the perspective earthquake.

2. Model formulation

The proposed model involves discussion about attenuation equation, site parameters, and model assumptions as presented below.

2.1. Attenuation equation

Ground motion intensity at a certain site is often correlated to earthquake magnitude, hypocentral distance, fault type, fault orientation, and local soil conditions (Villaverde 2009). It can be estimated with the help of attenuation relationships. Most attenuation relationships are developed using regression analysis, using data from previously measured strong ground motions. The functional form of equations is usually selected to reflect the underlying mechanism that gives rise to the ground motions (Villaverde 2009). The functional form is often expressed as:

$$\ln(Y) = C_1 + C_2 M + C_3 \ln(R + C_4) + C_5 R + C_6 f_1(\text{source}) + C_7 f_2(\text{soil})$$

(1)

where, the symbols have the following meanings:

- $Y$: Spectral ordinates / PGA / PGV
- $M$: Magnitude of earthquake
- $R$: Distance to source
- $f_1(\text{source})$: Dependent on characteristics of the fault responsible for the earthquake
- $f_2(\text{soil})$: Parameters (like $V_{S30}$) that are dependent on the site where the ground motion is being evaluated
- $C_i$: Regression coefficients

Using previous earthquakes’ response spectrum, regression models are developed to estimate regression coefficients for different time periods to essentially estimate spectral ordinates for any given values of the above-mentioned parameters. In this study, as the results are based on the active tectonic region of Himalaya, we consider the ground motion prediction equation (GMPE) provided by Akkar et al. (2010). The parameters for this model is described by the region type (active tectonic region), intensity measure types (PGA, PGV), site parameters ($V_{S30}$), rupture parameters (rake angle and earthquake magnitude), and distance measure type (Joyner-Boore distance, $R_{JB}$). A schematic diagram of an individual seismic source with its other properties is presented in Figure 1.

2.2. Site parameters

This step involves defining distance metrics and rupture related parameters for an assumed site. These distance measures are: (1) The straight distance between a site and the rupture plane (the rupture distance, $R_{RP}$), (2) the shortest distance from a site to the surface projection of the rupture surface (the Joyner-Boore distance, $R_{JB}$), and (3) The shortest horizontal distance from a site to the strike line

\begin{align*}
\text{Boore distance, } R_{BP} & = \sqrt{\frac{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}{d^2}} \\
\text{GMPE distance, } R_{GMPE} & = \frac{1}{d} \left[ \left| \frac{a}{a_{ref}} \right|^n \right] \\
\text{Rupture distance, } R_{RP} & = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \\
\text{GMPE distance, } R_{GMPE} & = \frac{1}{d} \left[ \left| \frac{a}{a_{ref}} \right|^n \right] \\
\text{Joyner-Boore distance, } R_{JB} & = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \\
\text{Horizontal distance, } R_{H} & = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}
\end{align*}
defined by extending the fault trace to infinity in both directions (the site coordinate, $R_X$); note that values on the hanging wall are positive and those on the foot wall are negative. The three rupture parameters for a fault are the dip angle ($\delta$), width of down-dip rupture ($W$), and rupture from depth to top ($Z_{TOR}$) (Kaklamanos et al. 2011; Demircioglu et al. 2018). A realization of these three distances and three rupture parameters are illustrated in Figure 2(a) at a hanging wall site.

In order to evaluate the most credible directions, hypothetical earthquakes were generated over a distance of 100 km from the centre of the projection of top edge of fault line. Thus, the footwall (FW) belongs to the first two quadrants ($0 \leq \theta \leq \pi$), whereas the hanging wall (HW) belongs to the next two quadrants ($\pi \leq \theta \leq 2\pi$) as illustrated in Figure 2(b). Several mathematical equations to relate the parameters may be derived from the illustration of Figure 2 (Villaverde 2009), though we have purposefully skipped such descriptions here.

**Figure 1.** Schematic diagram of individual seismic source with its other properties; top depth and bottom depth are the top and bottom depths of the considered fault; LL: lower left; LR: lower right; similarly, for UL, UR, SL, and SR (Basili et al. 2008).

**Figure 2.** (a) The schematic representation of the three distance metrics and three parameters associated with the fault rupture for a hypothetical site; (b) top view of the fault plane represented in polar coordinates ($r, \theta$); $L$ is the length of the fault (Kaklamanos et al. 2011).
2.3. Assumptions for analysis

To develop the MCD for a scenario-based event, we consider an earthquake of moment magnitude $M_w$ 6.85 and the fault parameters corresponding to the Himalayan Boundary Thrust (MBT). The three rupture parameters for the MBT are $\delta = 29^\circ$, $W = 10\, \text{km}$, and $Z_{TOR} = 3\, \text{km}$. The length of the fault is more than 2000 km, with rake angle $94^\circ$ and strike angle $290^\circ$ (Sharma et al. 2020). However, for computational simplicity, we consider the fault length as 40 km.

With the above considerations, a circular mesh of 100 radii was created, each with a concentric circle of a fixed radius $i$, containing either $100(i+1)$ points in case of PGA or $50(i+1)$ points in case of PGV, distributed uniformly on the corresponding concentric circles. A MATLAB code was developed for constructing mesh-grids, whereas Python scripts were written for performing natural interpolation on CSV data. The results are provided in the next section.

3. Results and discussions

As mentioned earlier, we consider the GMPE given by Akkar et al. (2010) for a constant $V_{S30}$ profile of 1200 m/s associated with a rocky soil base, and the associated spectral ordinate is taken to be peak ground acceleration. With this setting, the PGA at grid points for the MBT is pictorially represented in Figure 3(a), whereas the MCD for the PGA at grid points with constant $V_{S30}$ profile for the MBT is shown in Figure 3(b).

![Figure 3](image-url)

From Figure 3(b), it is observed that the model generates three ranges of directions measured at a distance of 20 km from the centre in which peak ground acceleration attenuates with the slowest rate. Moreover, we note that there are two directions of steepest descent (attenuation) in between these...
three ranges of MCDs. Also, we notice another interesting phenomenon at a distance of 22.14 km from centre in which the directions fork into two parts at angles of 334° and 200°. Moreover, the first fork at 200° furthers dissects itself into directions that curve the converge to 187° and 260°, whereas the other fork at 334° furthers dissects itself into directions that curve the converge to 281° and 354°. Therefore, we observe that PGA attenuation varies with different angles and radial distances, indicating the dependency between direction of propagation and earthquake origin characteristics.

4. Summary and conclusions
In this study, we have presented a relationship between fault source characteristics and the most credible direction of any earthquake that occurs at the source. For this, we have discussed attenuation equations, site parameters, and associated model assumptions corresponding to the Main Boundary Thrust. We derived peak ground acceleration and the most credible direction for the peak ground acceleration for a hypothetical earthquake. It was observed that the implemented model generates three ranges of maximum credible directions with a forking nature at two places. Therefore, the present study has successfully implemented the directional effect of strong ground motion.

Although we have derived surface curves assuming constant parameters for sites, a similar real-time MCD estimation can be performed by considering the actual soil profiles around the source. The analysis can also be carried out for different response time periods just by changing regression coefficients for the appropriate frequency. This will lead to obtain credible directions for the respective response time periods for a particular fault to enable risk analysis of selected monuments of national importance.

5. References
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