Macro-Level Assessment of Seismically Induced Landslide Hazard for the State of Sikkim, India Based On GIS Technique

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Abstract. This paper presents a macro-level seismic landslide hazard assessment for the entire state of Sikkim, India, based on the Newmark’s methodology. The slope map of Sikkim was derived from ASTER Global Digital Elevation Model (GDEM). Seismic shaking in terms of peak horizontal acceleration (PHA) at bedrock level was estimated from deterministic seismic hazard analysis (DSHA), considering point source model. Peak horizontal acceleration at the surface level for the study area was estimated based on nonlinear site amplification technique, considering B-type NEHRP site class. The PHA at surface was considered to induce driving forces on slopes, thus causing landslides. Knowing the surface level PHA and slope angle, the seismic landslide hazard assessment for each grid point was carried out using Newmark’s analysis. The critical static factor of safety required to resist landslide for the PHA (obtained from deterministic analysis) was evaluated and its spatial variation throughout the study area is presented. For any slope in the study area, if the in-situ (available) static factor of safety is greater than the static factor of safety required to resist landslide as predicted in the present study, that slope is considered to be safe.

1. Introduction
Landslide hazard poses major threat to most of the hilly regions in the world. In India, about 15% of the total land area (approximately 0.49 million km²) is susceptible to landslides. Regions which are highly susceptible to landslide are the Himalayas, North-east India and the Western Ghats NDMA, 2009). Mountainous topography, very high regional seismicity and high rainfall, make the Himalayan region and Northeast India highly susceptible to landslides. The present study makes an attempt to assess seismically induced landslide hazard at a macro-level for Sikkim, a state in India, situated in the Himalayas (fig.1). Several studies have showed that the Himalayan belt, which is an active plate boundary due to the convergent movement between Indian plate and Eurasian plate, is one the most seismically active regions in the world. The 2011 earthquake of magnitude (Mw) 6.9 along India-Nepal border, has triggered more than 300 landslides in Sikkim, affecting transportation and power infrastructures in the state (Chakraborty et al., 2011). The recent devastating earthquake of Nepal with a magnitude of 7.8, has also triggered landslides in the state of Sikkim. All this suggests a pressing need for a quantitative, macro-level seismic landslide hazard assessment for the state of Sikkim, in order to identify the regions with high hazard. The landslide hazard mapping provides decisive information to identify the landslide vulnerable regions, thereby effectively implementing the appropriate mitigation works.
2. Study Area and Seismicity
The state of Sikkim lies in a high seismic zone along the Himalayan belt. It is situated very close to the rupture zone of the 1934 M=8.4 Bihar-Nepal earthquake which is one of the most devastating earthquakes in the region. All the earthquake events within 500 km radius from the boundary of the study area were collected along with epicentral coordinates, focal depth, magnitude, date, time, and year of occurrence. Figure 2 presents the declusted earthquake event map within 500 km from the boundary of the state. Declustering was carried out in order to remove any repetitive events, foreshocks, aftershocks. After declustering, there are about 2830 seismic events occurred in the study area from 1901 to 2014, out of which 943 events are of magnitude 4 and above. There are about 11 events in the study area, having magnitude above 7. And from these, it is very clear that the Sikkim state is located in very high seismically active region Himalayas, where large magnitude earthquakes have occurred in the past.

3. Deterministic Seismic Hazard Analysis
As the literature suggests, there are two methodologies for estimating the seismic hazards at a site they are, Probabilistic Seismic Hazard Analysis (PSHA) and Deterministic Seismic Hazard Analysis (DSHA). The DSHA considers maximum magnitude-distance scenario at a shortest possible distance to the site for quantifying seismic hazard. Since it only considers the critical scenario, the DSHA gives an upper bound value for the ground motion when compared with that of predicted by PSHA at lower return periods. Hence DSHA is more suitable for assessing seismic ground shaking for the critical structures like nuclear power plants, big dams, bridges, hazardous waste contaminant facilities etc. In the present study, the DSHA has been adopted for the evaluation of seismic hazard.

Seismic hazard assessment using a deterministic methodology typically involves the following steps.
   i. Identification and characterization of all earthquake sources in the study area.
   ii. Selection of source to site distance. Generally the shortest possible distance between the source and the site (hypocentral distance) is considered for hazard estimation.
iii. Estimation of seismic hazard at a site from all known seismic sources using appropriate attenuation models or predictive relations.

iv. Selecting the critical value of ground shaking produced from all the sources as the seismic hazard of that site

![Image: Earthquake events within 500 Km from the Sikkim’s boundary]

**Figure 2.** Earthquake events within 500 Km from the Sikkim’s boundary

The seismic hazard at location is also dependent on the seismic source model used for the analysis. A seismic source model primarily defines the spatial characteristics of a source and the earthquake distribution within it. In the current study, the hazard analysis was carried out using the point source model. In a point source model, the location of an earthquake event itself is considered as a seismic source, thus, characterizing its geometry as a point. The point source model is simple and can very well characterize the earthquakes associated with a small fault or volcanoes. In spite of its simplicity, the point has been observed that the conventional point source model is always associated with some location error. Hence a smoothing procedure is applied to account for the source dimension of the earthquake events and for location errors (Costa et al., 1993; Panza et al., 1999).

The attenuation relation proposed by Sharma et al. (2009) for the Himalayan region (as in equation 1) has been used in the present study for evaluating PHA. Attenuation models or predictive relationships usually express the ground motion parameter as functions of magnitude, distance etc., which are generally developed from a strong motion data set based on regression analysis.

$$\log(y) = b_1 + b_2 M + b_3 \log\left(\sqrt{R_{jb}^2 - b_4^2}\right) - b_5 S + b_6 H$$  \hspace{1cm} (1)

Where $b_1$, $b_2$, $b_3$, $b_4$, $b_5$ and $b_6$ are the regression coefficients, $y$ is spectral acceleration in terms of m/s$^2$ and $S$ is 1 for rock site, $H$ is 1 for strike-slip and 0 for reverse mechanism $M$ is the earthquake magnitude and $R_{jb}$ is Joyner-Boore distance.

3.1. Hazard Assessment

A MATLAB program was developed to compute hazard parameter mainly PHA for the study areas. The major steps involved in the deterministic hazard assessment are presented below.
1. All the earthquake sources within 500 km radius from a particular grid point were considered in the program for evaluating seismic hazard.

2. The minimum distance from the selected grid point to each of the sources was calculated. The focal depth was taken as 15 km.

3. Considering the maximum magnitude and the minimum possible hypocentral distance, the PHA values for the given grid point, were calculated using attenuation relation for each of the sources.

4. The maximum of these PHA values was taken as the PHA for that particular grid point.

5. Similar analysis was done for all the grid points and the PHA values were obtained.

Figure 3 presents the spatial variation of PHA values at the bedrock level, throughout the state of Sikkim. The PHA value at ground surface for each grid point was estimated using a non-linear site amplification technique (Stewart et al., 2003; Raghu Kanth and Iyengar, 2007). The surface level PHA was estimated for grid points which are having slope value greater than or equal to 10 degrees. The grid points having slope angle less than 10 degree were considered to be flat and hence neglected. The site class for the grid points having slope angle 10 degree and above (gradient ≥ 0.176 m/m) was found to be B-type (Wald and Allen, 2007) for which the average shear wave velocity for top 30 m overburden ($V_{s30}$) is more than 760 m/s (BSSC, 2003) The PHA at the ground surface $Y_g$ for a particular grid was evaluated by multiplying suitable amplification factor $F_s$ by the bedrock level PHA ($Y_{br}$) as shown in equation 2.

$$Y_g = Y_{br} \times F_s$$  (2)

Raghu Kanth and Iyengar (2007) have developed a regression relation (eqn.3) for determining amplification factor $F_s$.

$$\ln(F_s) = a_1 Y_{br} + a_2 + \ln(\delta_s)$$  (3)

For site class B, $a_1 = 0$ and $a_2 = 0.49$ are site class dependent regression coefficients, $Y_{br}$ is the spectral acceleration at bedrock level and $\delta_s = 0.08$ is the error term as per Raghu Kanth and Iyengar (2007).

4. Development of Slope Map

Digital elevation models (DEMs) are raster data files containing terrain information for a specified region in form of pixels (fig. 4(a)). The resolution of the DEM refers to the distance between two adjacent pixels. The ASTER Global Digital Elevation Model (ASTER GDEM) was developed and released by the Ministry of Economy, Trade, and Industry (METI) of Japan, with the collaboration of National Aeronautics and Space Administration (NASA) United States, covering about 99% of the total land area with a resolution of 1 arc-second (30 m). The slope map of the study area was developed from ASTER DEM using ArcGIS 10 (fig. 4(b)).

5. Landslide Hazard Assessment

Several studies have showed that the Newmark’s sliding-block model is the most viable method to assess seismic landslides on natural slopes (Wilson, 1983; Wilson and Keefer, 1985; Wieczorek et al., 1985; Jibson, 1993). Wilson and Keefer (1985) showed that the Newmark’s method results in a less conservative and more cost effective design than the pseudostatic methods and thus most appropriate for predicting landslide in a natural slope. In the Newmark’s method, the soil mass at failure is modelled as a rigid block sliding along an inclined plan, where the resisting forces is just been exceeded by driving forces. Hence the factor of safety drops below 1.0 (Kramer, 1996) and the block requires a critical acceleration ($a_c$) as per equation 4 which is the threshold acceleration to initiate sliding (Jibson et al., 2000).
Here FS is the static factor of safety, which depends on the in-situ soil parameters and slope angle (α). In the present study, landslide hazard is predicted in terms critical value of factor of safety (FS<sub>c</sub>) required to resist landslide was evaluated as per equation 5 against a destabilizing force generated by surface level shaking obtained from the DSHA. The slope is considered to be safe, if the in-situ static factor of safety is greater than the computed critical static factor of safety (FS<sub>c</sub>).

\[
FS = \frac{PHA}{\sin \alpha} + 1
\]

The study area is first divided into 4 districts and the seismic landslide hazard map of each district was developed considering a grid size of 30 m × 30 m size. The landslide hazard maps of all 4 district are then merged, to obtain the landslide hazard map of Sikkim. The slope angle value for each grid point was derived from ASTER DEM, using GIS. Knowing the seismic acceleration and the slope angle, the static factor of safety (FS<sub>c</sub>) required to resist landslide is evaluated for each grid point. The static factor of safety for any slope depends upon the in-situ soil parameters such as shear strength, density and slope angle etc., which can be evaluated using conventional slope stability analysis. A high value of static factor of safety for a slope implies a higher stability of the slope against earthquake shaking. Thus if the in-situ static factor of safety is greater than the computed static factor of safety (FS<sub>c</sub>) required to resist landslide, the slope is considered to be safe. Figure 5 presents the landslide hazard map of Sikkim, showing the spatial variations of the critical static factor of safety required to resist landslide throughout the state.

\[
a_c = (FS - 1)g \sin \alpha
\]
Figure 4. (a) Digital Elevation Model and (b) Slope map of the study area

Figure 5. Seismic landslide hazard map of Sikkim
6. Conclusions
The present study describes the quantitative evaluation of seismic landslide hazard for the entire state of Sikkim in terms of static factor of safety required to resist landslide, based on the Newmark’s method. Topographic slope map for the entire state of Sikkim was derived from the ASTER GDEM. Peak horizontal acceleration (PHA) at ground surface, obtained from DSHA, is used as critical acceleration for evaluating static factor of safety to resist landslide. This paper presents a landslide hazard map of Sikkim, showing the spatial distribution static factor of safety required to resist landslide. For a given natural slope, located within the state of Sikkim, the in situ static factor of safety for that slope can be computed using conventional slope stability analysis. The static factor of safety based on dynamic finite element method is recommended for evaluating dynamic slope stability. Thus the map developed in the present study is an excellent first level landslide inventory database, which is helpful for a quick assessment of seismically induced landslides while planning big projects like new road/rail routes, setting up power generation/transmission structures, tunnels etc.

The present study classifies Sikkim into 3 hazard zones based on the range of static factor of safety required to resist landslide. They are, low hazard region (1.0< FS<1.5), moderate hazard (1.5< FS<2) and high hazard (FS≥2.0 and above). From fig. 5, it can be observed that majority of Sikkim falls in high hazard zone, where a minimum static factor of safety of 2.0 and above against an expected earthquake ground shaking, to resist landslide. Such a high value of seismic landslide hazard is due to high level of expected ground shaking ranging from 0.2g to 0.3g at bedrock level and steep terrain. Hence it is highly recommended to carry out a rigorous micro-level landslide hazard assessment for hilly region in the state were human settlement is high. The current landslide hazard map for the state of Sikkim has been developed based on 110 years of earthquake data, hence it requires revision after any major earthquake, occurred within the radius 500km from the boundary of Sikkim.

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