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Comparative study of seismic hazard of Kathmandu valley, Nepal with other seismic prone cities

Étude comparative des risques Sismiques de la vallée de Katmandou, Népal avec d'autres villes a risques

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ABSTRACT
Probabilistic seismic hazard analysis for Kathmandu valley is carried out by using historical earthquake records for 400 km radius available from USGS-NEIC. Based on the attenuation relations developed by Chang et al. (2001) the earthquake hazard level for the valley is found to be comparable to the hazard prone cities like Sendai of Japan and Los Angeles of USA. The estimated PGA levels for different return periods are also compatible with the available results of Global Seismic Hazard Analysis Program.

RÉSUMÉ
L'analyse probabiliste de risque sismique pour la vallée de Katmandu est effectuée en employant les données historiques des tremblements de terre sur un rayon de 400 kilomètres fournies par l'USGS-NEIC. Basé sur les relations d'atténuation développées par Chang et autres (2001), le niveau de risque de tremblement de terre pour la vallée est comparable à ceux des villes à risque comme la ville de Sendai, Japon et la ville de Los Angeles, Etats-Unis. Les niveaux estimés de PGA pour différentes périodes de retour sont également compatibles avec les résultats disponibles au Programme Mondial d'Analyse des Risques Sismiques.

1. INTRODUCTION

Kathmandu valley consists of three major cities including the capital city making it a major urban center of Nepal with population of around 1.5 million. The land area of the valley is about 583 square km and it is nearly circular in shape with an average diameter of 30 km. There is a high risk of earthquake damage of residential buildings and urban infrastructures due to following reasons: (1) The valley is close to the major Himalayan faults like Main Central thrust; (MCT) and Main Boundary thrust (MBT) resulting in high seismicity. (2) The valley consists of very soft lacustrine soil with estimated depth of 300-400 m; (3) The topography of the valley is susceptible to amplification of seismic waves due to basin effects; (4) There are many non-engineered structures prevailing in the city that are highly vulnerable to earthquake damage. Kathmandu valley experienced a destructive earthquake in 1934 with estimated surface wave magnitude of 8.3. Although the epicenter of this earthquake was about 178 km away from the valley, there was devastating damage in the urban area. It is believed that the intensity in the valley was higher than in the area believed to be epicentral region. The reason may be due to the geological and topographical setting of Kathmandu. It is observed from the past trends that earthquakes of similar magnitude repeat in several decades in the Nepal Himalayas and adjacent area (Pandey et al 1999). Thus there is an urgent need of evaluating hazard potentials of Kathmandu valley incorporating topographical, structural and subsoil conditions aiming the preparedness for seismic risk.

This paper summarizes the preliminary results of the risk analysis of urban infrastructures aiming to develop a strategy for microzonation of Kathmandu valley. The result of probabilistic seismic hazard analysis has been compared with two widely known seismic prone cities of the world, Sendai of Japan and Los Angeles of USA, both lying in the two sides of the Pacific coasts. By this comparison of the seismic hazard of Kathmandu valley obtained from this study, it is expected that the risk scenario may be estimated with reasonable reliability and providing the basis for understanding of hazard level obtained from the seismic hazard analysis.

2. PROCEDURE OF SEISMIC HAZARD ANALYSIS

Probabilistic seismic hazard analysis involves computation of annual rate of exceedance of certain peak ground motion parameter of earthquake. Peak ground acceleration (PGA), the commonly used peak ground motion parameter, is considered in this study. The widely used method of carrying out probabilistic seismic hazard analysis involves computing the value of the constant λ_{y*} in the Poisson equation $P[Y > y*] = 1 - e^{-\lambda_{y*}t}$ where P[Y>y*] is total probability of occurring of an event with Y> y* and λ_{y*} is the mean annual rate of being exceeded (Kramer 1996). The relation for λ_{y*} is

$$\lambda_{y*} = \sum_{i=1}^{N_s} \nu_i \iint P[Y > y*/m,h] f_{Mi}(m) f_{Hi}(h) dm dh \quad (1)$$

where, N_s = number of earthquake source zones, ν_i = 10^{a-bm0} for *ith* source, 'a' and 'b' being constant of recurrence curve, m_0 is the minimum threshold magnitude, m = earthquake magnitude, h = source-site distance, $f_{Mi}(m)$ = probability density function of magnitude, $f_{Hi}(h)$ probability density function of distance. The process involved in computation of λ_{y*} is described stepwise in the following subsections starting from the earthquake data used.

2.1 *Earthquake data*

The seismic network of Nepal was established in 1985 and limited information of hypocenters is available from this network of seventeen seismographs (Pandey et al. 1999). The hypocenter solutions are available for earthquakes occurring after the year 1985. The information, however, is not sufficient to carry out seismic hazard analysis that ideally requires continuous data for at least several decades. The data from

United States Geological Survey–National Earthquake Information Center (USGS-NEIC) has been downloaded for a rectangular area surrounding Nepal. From this data, earthquakes within 400 km radius of Kathmandu valley are queried as two datasets as follows: (1) Pre-instrumental dataset for the year 1904-1972. Adding some instrumental records of period 1973-2003 having magnitude greater or equal to 5.0, this dataset covers for a period of 100 years. (Fig. 1a). (2) Instrumental data for the period of 1973-2003 (Fig. 1b). This dataset is commonly known as preliminary determination of epicenters (PDE) database. The features of both datasets are given in Table 1. The numbers of earthquakes in pre-instrumental dataset is less because only earthquakes with magnitude greater than 5.0 can be found in the period between 1903-1972. This data is used to find the 'a' and 'b' values in recurrence curve as shown in Figure 2(a). The distribution $f_{Mi}(m)$ is assumed to follow bounded Gutenberg-Richter relation (Kramer 1996) as in Figure 2(b).

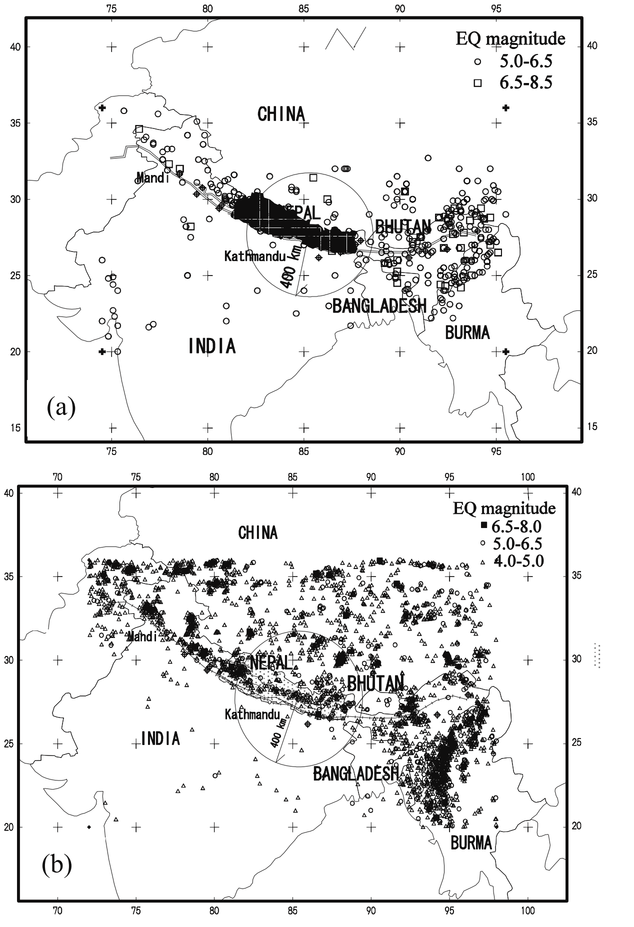

Figure 1. (a) Pre-instrumental data (b) Instrumental data (PDE)

Table 1. Main characteristics of two datasets of earthquakes

Dataset	Period	Magnitude (Mw)	Earthquakes within 400 km of Kathmandu valley
Pre-instrumental	1904-2003	5.0 – 8.0	51
Instrumental	1973-2003	4.0 – 6.8	381

The probability density function $f_{Hi}(h)$ is assumed to be consistent with the previous rate of earthquake occurrence at various distances from Kathmandu valley. This means that earthquakes in the future will occur in same proportions in distances what they have occurred up to now. Figure 2(c) shows the distribution $f_{Hi}(h)$ for two periods. It shows that the rates of occurrences of earthquakes with respect to distance are not very different despite the differences in numbers as observed in Figure 2(c) for two datasets.

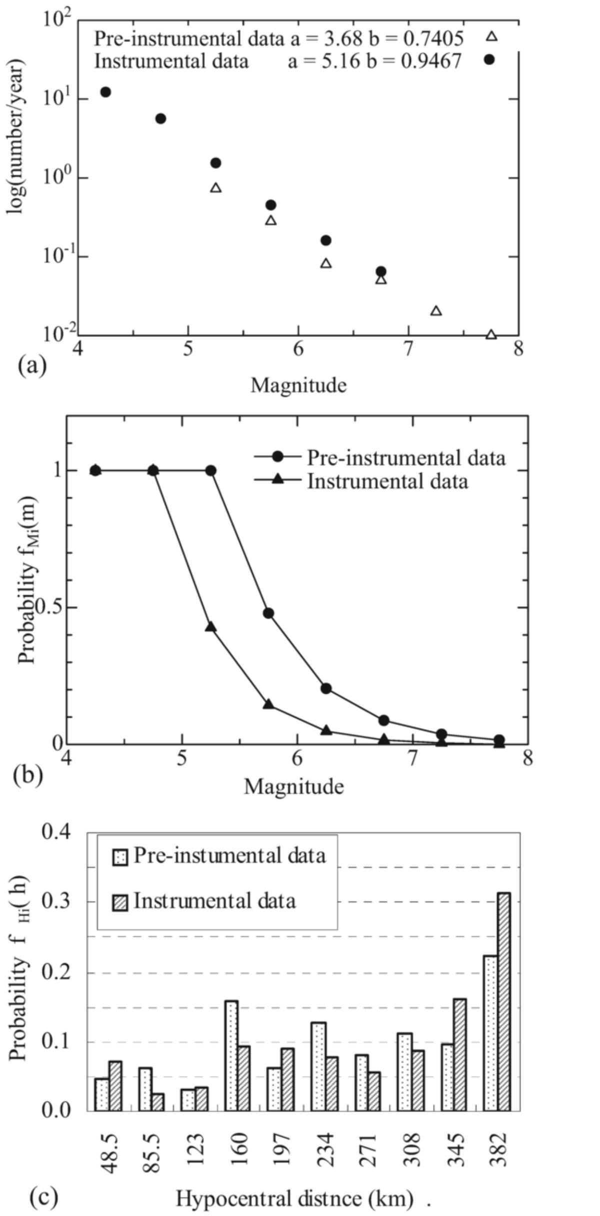

Figure 2 (a) Plot of recurrence curve (b) Bounded Gutenberg-Ritcher plot showing $f_{Mi}(m)$ (c) Source-site distance to represent $f_{Hi}(h)$

2.2 *Attenuation relationship*

Attenuation relationship is needed to evaluate P[Y>y*/m,h] so that predictive value of peak ground motion parameter is known for assumed magnitude and epicentral distance. The choice of attenuation relation is the crucial step in the process of carrying out seismic hazard analysis. There is no known attenuation relationship developed for Nepal Himalaya and also no known strong ground motion recording instrument in this area.

In the absence of attenuation relationship for Nepal Himalayas, recently developed attenuation relationship by Chang et al. (2001) for crustal earthquakes has been used in this study. Although this attenuation relationship was developed for Taiwan, the attenuation characteristics of Himalayan earthquakes are found to be similar in limited observations. This observation is from the limited acceleration records of Chamoli earthquake (1999) recorded in Garhwal Himalayas (west of Nepal Himalayas). Since the attenuation relationship used is intended for firm soil or rock, the result is also obtained for the rock site. The attenuation relationship by Chang et al (2001) for crustal earthquakes is:

$$\ln PGA = 2.8096 + 0.8993 M_w - 0.4381 \ln D_f - (1.0954 - 0.00790 D_f) \ln R$$
$$\sigma(\ln PGA) = 0.60 \qquad (2)$$

where, M_w = moment magnitude, D_f = focal depth in km and R is the epicentral distance in km, σ = standard deviation.

3. ESTIMATED PGA FOR ROCK SITE

The attenuation relation by Chang et al (2001) gives the relations for rock site without information of local site effects. Calculation of annual exceedance probabilities by integrating Equation (1) is carried out for PGA levels of 0.01g, 0.05g, 0.1-1.0g for the two datasets. The result is given as hazard curves for Kathmandu as shown in Figure 3. The hazard curve for Sendai city is obtained from the earthquake data of Japan for 76 years, details of which is given in Sunuwar et al. (2003).The hazard curve of Los Angeles city of USA taken from Thiel (2002) is also depicted for comparison. The comparison in Figure 3 shows that the annual hazard curve for Kathmandu is slightly lower but comparable to that of Sendai city and Los Angeles city. It is slightly higher than that of Los Angeles city for PGA<0.2g. It can be said that with limited historical earthquakes of short duration of 31 years, the earthquake hazard level is comparable to typical earthquake prone locations lying in the highest seismic zones of the world. The exceedance rate of small events occurring in the vicinity of Kathmandu valley is higher than that of Los Angeles city but lower than that of Sendai city. When earthquakes for longer duration are considered using pre-instrumental dataset, the hazard is lower than that of Instrumental data as shown in Fig. 3. The reason for low hazard may be the omission of earthquakes which are far from habitated areas in the pre-instrumental data.

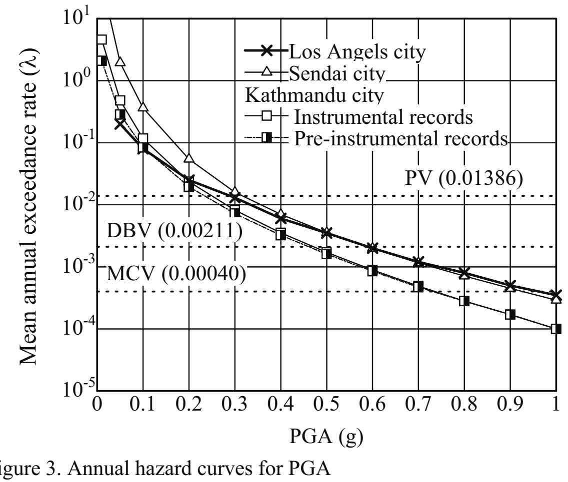

Figure 3. Annual hazard curves for PGA

Table 2 shows the various levels of PGA with 2%, 10% and 90% probability of being exceeded in 50 years in Kathmandu valley for two datasets. These values are termed as maximum considered value (MCV), design basis value (DBV) and probable value (PV)respectively. The probability levels associated with these values are depicted in the parenthesis in Fig. 3. For example, the level of PGA for 2% probability of being exceeded is 0.72g for the pre-instrumental dataset. The corresponding value is 0.76g when instrumental dataset is used. The result of this study for Kathmandu valley with about 0.5g as DBV is higher than the result of GSHAP in which DBV of the valley is in the range between 0.40-0.45g (Bhatia et al 2000). GSHAP study has considered all Indian subcontinent for seismic hazard analysis and presented the result in the form of hazard map. Another hazard map by Pandey et al. (2002) shows the DBV of only about 0.2g for the valley using attenuation relationship by Youngs et al. (1997). However, the length of historical records are not given by authors. Unlike these two studies, this study has considered the earthquakes surrounding Kathmandu valley from which values like MCV, DBV, and PV are summarised that may be useful for design practices.

Table 2 PGA (g) that has probability of being exceeded in Kathmandu

Dataset	Pre-Instrumental	Instru-mental
2% probability of being exceeded (MCV)	0.72	0.76
10% probability of being exceeded (DBV)	0.47	0.49
50% probability of being exceeded (PV)	0.25	0.26

4. SOIL CONDITION IN KATHMANDU VALLEY

The detailed geotechnical data of lacustrine deposits of Kathmandu valley is not available in a comprehensive manner and thus scattered information has to be gathered from different sources. The recent engineering and geo-environmental map by Shrestha et al. (1998) shown in Figure 4 gives some details of geological profiles of soil types existing in Kathmandu valley. There are altogether 19 types of geological formation with local names depicted in the map and the important formations are shown in Table 3. From this map, it can be observed that most of the urban settlement in the valley is over the formation *'klm'*, *'gkr'* and *'cpg'*. The formation *'sal'* is in the margin of river where new settlement is emerging encroaching the river. All three *'klm'*, *'gkr'* and *'cpg'* formation are of the plio-pleistocene age. The formation *'sal'* consists of recent sediments of flood plain and belongs to the quaternary formation. The formations *'klm'* and *'sal'* are said to have low bearing capacities requiring precautions and special care in constructing foundations (Shrestha et al. 1998). Another feature that can be observed from Figure 4 is that the geological formations in the boundary of Kathmandu valley generally belong to group of hard rocks. For example: the formations *'sgn'*, *'ku'* and *'ti'* are in the boundary of valley as depicted in Table 3. It can be expected from the pattern that the valley has relatively stiff material as the base of the basin. It has been confirmed by boring in several places (Sakai 2001).

Observing the soil conditions of Kathmandu valley it can be said that most of the foundations of structures are founded in soft soils. Foundations in soft soils are quite susceptible to damage due to seismic ground motion. From Table 3, it can be said that dominant types of the soils in the first five geological formations are fine-grained soils like clay and silt. The likely values of shear wave velocity (V_s) for the top five formations except 'sal' type could range from 165-300 m/s from the Japanese experience of Japan. For this range of V_s the resulting amplification in PGA may be double of that observed in hard rocks (Midorikawa et al. 1994). Thus the PGA values calculated in the previous section may become higher due to the site effects. In addition to this, the topography of valley is bowl shaped and the basin is formed in relatively firm rock (Sakai 2001). This may result amplification of seismic surface waves due to rebounding effects. The detailed study of this effect can be a further topic of research.

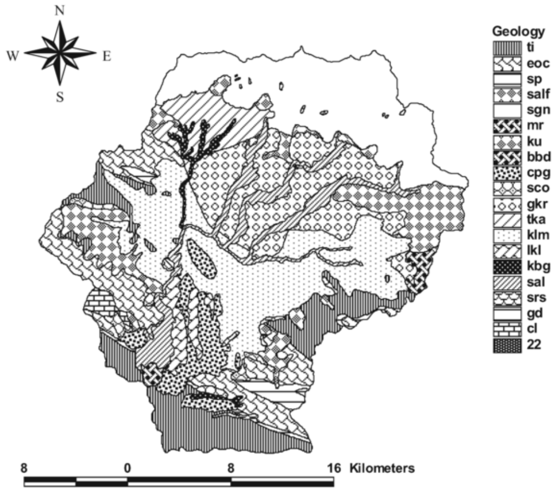

Figure 4. Main geological formations of Kathamndu valley (Modified from Shrestha et al. 1998)

Table 3. Man geological formations of Kathmandu valley

Formation	Main soil types	Approx. depth
klm (Kalimati)	Silty clay and clayey silt	450 m or more
gkr (Gokarna)	Poorly graded silty sand	300 m or more
cpg (Chapagaon)	Sandy gravel	Up to 110 m
sal (Recent alluvial)	Clay, sand and fine gravel	Very shallow
tka (Tokha)	Sandy clay	200 m
sgn (Shivauri)	Muscovite granite	
ku (Kulekhani)	Biotite schist	2000 m
ti (Tistung)	Phyllite	3000 m

5. SEISMIC RISK OF KATHMANDU VALLEY

Seismic risk is a combination of hazard and vulnerability. This study reveals that high level of PGA is expected for Kathmandu valley, which may further increase by the amplification of local soft soil. The hazard level is comparable to that of the major earthquake prone cities of the world. On the other hand, compared to well-designed stocks of infrastructures in the Sendai and Los Angeles cities, Kathmandu valley has very few infrastructures that are designed and constructed for seismic safety. The reluctance of the authorities to strictly implement the earthquake resistant design code even today clearly shows the negligence to earthquake hazards and its consequences. This situation leads to a high vulnerability of infrastructures present in Kathmandu valley.

Previous report from Kathmandu valley Earthquake Risk Management Project (KVERMP 1999) also alerts for heavy damage of infrastructures. According to the report, the intensity of 1934 earthquake measured X in Modified Mercalli Intensity (MMI) scale. This high intensity was coupled with liquefaction at different sites, thus validating the severity of shaking potential as shown by probabilistic hazard analysis above. This indicates the increased levels of risk from geotechnical hazards triggered by earthquake in Kathmandu valley.

6. CONCLUSIONS

Probabilistic seismic hazard analysis has been carried out for Kathmandu valley considering two datasets of different durations. The results show that the PGA levels in rock sites are comparable to highly seismic prone cities like Sendai of Japan and Los Angeles of USA. In contrary to this, Kathmandu valley has highly vulnerable stocks of infrastructures than two other cities. This result will be useful in developing a strategy of seismic microzonation consisting of soft lacustrine soil deposit incorporating detailed geotechnical characteristics of the soil.

The preliminary observation of soil types of Kathmandu reveals that the soft soil is embedded in relatively hard rock bed resulting in a high succeptibility to ground motion amplification both due to site effect and basin effect. Further detailed study is needed in this area.

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