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RISK CONSISTENT RESPONSE SPECTRUM AND HAZARD CURVE FOR A TYPICAL LOCATION OF KATHMANDU VALLEY

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SUMMARY

The seismic hazard curve and the risk consistent response spectrum are obtained by a simplified method to identify the seismic hazard potential of the Kathmandu Valley, which is surrounded by a number of the active faults. The hazard curve and the risk consistent response spectrum at the bedrock level are obtained assuming the occurrence of earthquake as Poisson process using a number of attenuation laws available in the literature, and an empirical relationship of spectral ordinates with the magnitude of earthquake. The free field ground motion for some important sites is obtained by carrying out one dimensional wave propagation analysis considering both linear and nonlinear soil conditions. Major finding of the study shows the significant influence of the nonlinear behavior of the overlying soil in the nature of the free field hazard curve and response spectra.

INTRODUCTION

The Kathmandu Valley has long been recognized as one of the most seismically vulnerable area in the region because of its geographical location, peculiar neo-tectonic and geo-technical features. The ongoing neo-tectonic activity within the Kathmandu Valley is demonstrated by the presence of many active faults within and in the vicinity of the Valley.

The Kathmandu Valley, considered as an in filled basin, has sediment deposits of different layers varying in composition and depth from one part to another. The subsurface soil condition is dominated by unconsolidated sediments. One of the major factors influencing the level of ground motion within the Valley is the site amplification due to unconsolidated sediments.

The Kathmandu Valley has a long history of earthquakes. It has been subjected to frequent earthquakes of moderate intensities, and about once in a century to disastrous earthquake of higher magnitude. The strong ground shaking in the Valley due to the Great Nepal Bihar Earthquake of 1934 AD of magnitude M 8.4 Richter Scale resulted into damage intensity of IX – X MMI in many parts of the Valley.

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The seismic vulnerability of the Kathmandu Valley has been well recognized. Nevertheless, no systematic study has been made so far to identify the seismic hazard potential of the Valley; neither any work is reported to characterize the risk consistent response spectra to be used for analysis of structures in the region.

However, there have been a number of studies on the seismic risk of many cities of the world and on hazard analysis and risk consistent response spectra. Cornell [1] carried out seismic risk at a site in a probabilistic format in terms of PGA and return period. Der Kiureghian and Ang [2] proposed a fault rupture model for risk analysis. Fukushima et al. [3] developed a new attenuation relation for PGA applicable to the near source region in Japan. Cardona et el. [4] studied the seismic hazard and the urban seismic risk for Bogota, Colombia. Loh et el. [5] proposed a method for conducting a seismic hazard analysis in which the annual probability of exceedence at a site is calculated based on PGA attenuation formula. Takemura et al. [6] presented a method for seismic hazard evaluation, which deals with response spectrum information. Other important studies in the area include those by Benouar et al. [7], Loh and Ang [8], Budnitz et al. [9] and others.

With an objective to identify the seismic hazard potential of the region and the risk consistent seismic input for analysis of structures in this region, a simplified method for obtaining them is presented. The simplified procedure is illustrated by determining seismic hazard curves and risk consistent response spectrum of three sites located in Bhaktapur City, a typical area representing the Kathmandu Valley. The hazard curves and the risk consistent response spectrum both at the bedrock and free field are obtained. For obtaining the free field hazard curve and risk consistent response spectra the soil sediment is idealized as both linear and nonlinear medium, and a one-dimensional wave propagation analysis is carried out. The different characteristics of the hazard curves and the risk consistent response spectra are discussed.

SEISMIC HAZARD POTENTIAL OF A SITE

The seismic hazard potential of a site is identified typically by carrying out a probabilistic seismic hazard analysis and constructing seismic hazard curves. A seismic hazard curve, representing the relation between the seismic intensity parameter, such as, peak ground acceleration (PGA) and its annual probability of exceedence, is obtaining by synthesizing several types of information's. These information's include the identification of the earthquake sources in the vicinity of the site, the arrival rate of earthquake, probability density function of the earthquake magnitude, and the seismic intensity parameter, usually in the form of peak ground acceleration (PGA) at the site for probable earthquakes occurring at the sources.

The Kathmandu Valley is one of the regions which have a long history of earthquakes but do not have enough recorded earthquake data. The proposed simplified method, considering the situation, consists of the following components:

The seismic hazard curve is constructed following the procedure outlined by Cornell [1] and Der Kiureghian and Ang [2]. The annual occurrence rate of the intensity parameter ‘A’ (PGA) exceeding a specified value ‘a’ for a particular site is given by

$$\nu(A \geq a) = \sum_k \nu_k \sum_j \sum_i P(A \geq a \mid m_i, r_j) P_k(m_i) P_k(r_j) \quad \text{..........} \quad (1)$$

Where, $P_k(m_i)$ and $P_k(r_j)$ represent the probability mass function of magnitude and distance from site to earthquake sources at the k-th zone, respectively; ν_k is the annual occurrence rate of earthquakes in the k-th zone; and

$P(A \geq a|m_i, r_j)$ is the conditional probability of 'A' exceeding 'a' given m_i and r_j.

The events of earthquake occurrence are assumed to be independent of each other in time and space, that is, Poisson's Process, and accordingly the seismic hazard curve is obtained by the relation:

$$P(A \geq a) = 1 - \exp\{-\nu(A \geq a)\} \ldots\ldots\ldots\ldots\ldots(2)$$

Since the probability of occurrence of earthquakes of large magnitude is very less, the distribution function for magnitude of earthquake may be assumed to be a simple exponential distribution or Gumbel Type I distribution. In the proposed method the exponential distribution is adopted.

This type of probability distribution function of the magnitude of earthquake is based on the Gutenberg – Richter Recurrence Law:

$$\log \lambda_m = a - bm \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3a)$$

$$\lambda_m = 10^{a-bm} = \exp(\alpha - \beta_m) \ldots\ldots\ldots\ (3b)$$

Where, λ_m is the mean annual rate of exceedence of magnitude m;

10^a is the mean yearly number of earthquakes greater than or equal to zero; and b describes the relative likelihood of large or small earthquakes.

Equation (3b) implies that magnitudes are exponentially distributed.

The probability density function (PDF) of the magnitude of earthquake is given by:

$$P_M(m) = \beta e^{-\beta(m-m_o)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where, $\beta = 2.33b$, and m_o is the lower threshold magnitude of earthquake, earthquake smaller than which are eliminated, and m is the magnitude of earthquake.

RISK CONSISTENT SEISMIC INPUT

In the process of identification of risk consistent seismic input for analysis of structures in the region, a risk consistent response spectrum at the bedrock is first obtained. For the purpose, the risk consistent spectral shape is obtained by an empirical relationship, which relates the normalized ordinates of response spectrum in terms of the magnitude of earthquake and the source-to-site distance. The typical empirical attenuation equation of the spectral acceleration for the evaluation of spectral shape given by Takemura et al. [6] is:

$$l_n\ S_a(T) = a(T)M - b(T)l_n X + C(T) \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

in which $S_a(T)$ is the spectral acceleration at bedrock in cm/s^2, M is the magnitude of earthquake, X is the source-to-site distance in km, T is the time period in second, and a (T), b(T) and c(T) are coefficients that are determined by regression analysis of earthquake motions, and are given in the form of curves as shown in Fig. (1). These values are valid for normalized response spectrum corrected to 2% damping.

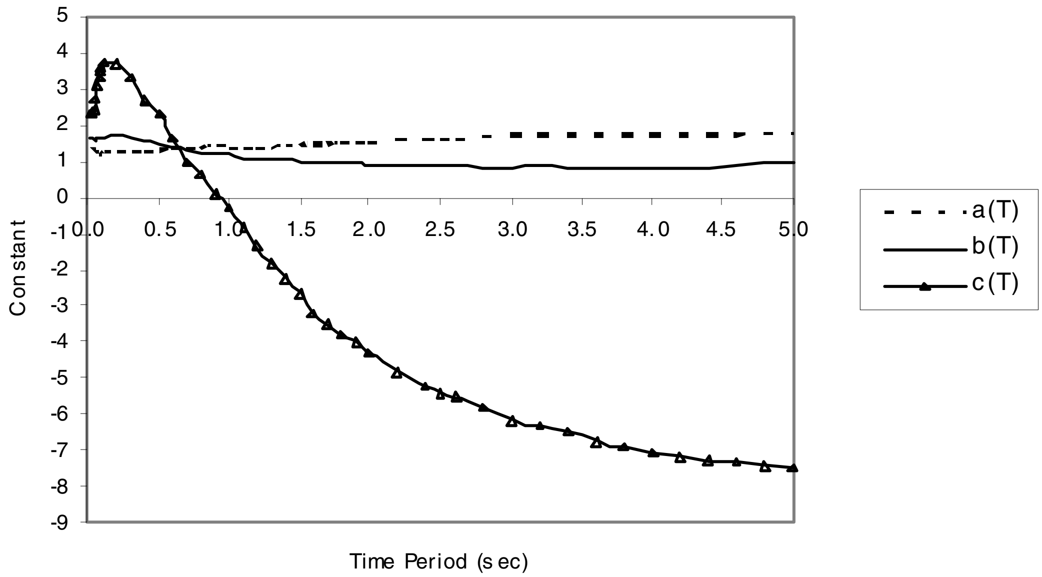

Figure 1. Variation of Constants with Time Period

The probabilistic estimation of the response spectra of ground motion is done by expanding the method to evaluate seismic hazard as described in section 2. In the method, it is assumed that a normalized response spectrum normalized by its maximum acceleration value $S_N(T)$ is an empirically determined function of magnitude M and distance R (epicentral or hypocentral), and, as a second order approximation that it is a log-normally distributed random variable. Accordingly,

$$S_N^{\ *} = l_n\, S_N\,(T) = l_n\, S_N\,(M,R,T) \text{ .... (6)}$$

in which, T represents the natural period.

The conditional probability mass function of magnitude and distance given that the intensity parameter A (PGA in the case) is between a_1 and a_2 due to an earthquake event in the k-th zone, denoted by $P_k\,(m_i,\, r_j\,/\,a_1 \prec A \le a_2)$ is given by

$$P_k\,(m_i, r_j\,/\,a_1 \prec A \le a_2) = \frac{P\big(a_1 \prec A \le a_2\,/\,m_i, r_j\big) P_k\,(m_i)\, P_k\,(r_j)}{P_k\,(a_1 \prec A \le a_2)}$$

$$= \frac{P\big(a_1 \prec A \le a_2\,/\,m_i, r_j\big) P_k\,(m_i)\, P_k\,(r_j)}{\sum_j \sum_i P(A \ge a \mid m_i, r_j)\, P_k\,(m_i) P_k\,(r_j)} \text{ .... (7)}$$

in which, $P_k(m_i)$ and $P_k(r_j)$ represent the probability mass functions of magnitude and distance from source-to-site distance at the k-th zone respectively. The conditional mean value of the natural logarithm of response spectrum for the k-th zone is given by:

$$\overline{S}^{*}_{NK} = E_k \left\{ S^{*}_{N}(T) \mid a_1 < A \le a_2 \right\}$$

$$= \sum_j \sum_i S^{*}_{N}(m_i, r_j, T) \, P_k(m_i, r_j \mid a_1 < A \le a_2) \text{ .... (8)}$$

The conditional mean value, considering all seismic zones, is given by:

$$\overline{S}_{N}(T) = E\left\{ S^{*}_{N}(T) \mid a_1 < A \le a_2 \right\}$$

$$= \sum_j \sum_i S^{*}_{N}(m_i, r_j, T) \; P_k(m_i, r_j \mid a_1 < A \le a_2) \text{ .... (9)}$$

Where, ν_k represents the annual occurrence rate of earthquake in the k-th zone.

LOCAL SOIL SEDIMENT EFFECT

The hazard curve and the risk consistent response spectrum obtained earlier are valid for bedrock condition or for the free field consisting of very firm soil layer extending from the source of earthquake to the site. The soil sediment, overlying the bedrock at the site, is to be taken into account for its amplification effect. The hazard curve and the risk consistent response spectrum for bedrock are modified considering the local soil amplification effect.

Modifications of the ground motion due to the local soil effect are essentially carried out by a one-dimensional wave propagation analysis. The soil profile above the bedrock is generally multi-layered having different soil properties in each layer. For a certain input excitation at the bedrock level some of these layers can undergo non-linear excursion. The one-dimensional wave propagation analysis is carried out by numerical integration of the equation of motion in the incremental form for a prescribed time history of acceleration at the bedrock level.

The PGA amplification due to the overlying soil is obtained considering two conditions, namely, (1) linear behavior of soil layers, and (2) some of the soil layers may undergo non-linear behavior with prescribed non-linear stress-strain relationships. The input ground motion is simulated from the risk-consistent response spectrum developed as described above. The simulation of the time-history of the ground acceleration at the bedrock is done by the method proposed by Khan [10]. When non-linear behavior of soil is taken into consideration the time histories of ground motion are generated for different PGA values within the range of interest. For non-linear soil condition, the PGA amplification depends upon the level of input PGA at the bedrock.

The free field PGA is obtained by multiplying the PGA at the bedrock level by the PGA soil amplification factor. The conditional probability in Eq. (1) is then modified by considering the free field PGAs in place of bedrock PGAs. The seismic hazard curves are accordingly modified to obtain the same for the free field. In order to obtain the risk consistent response spectra for free field ground motion the sample time history of input ground motion acceleration is directly generated from the normalized risk consistent response spectrum as described earlier. The time history of the free field absolute ground acceleration is obtained by integrating the equation of motion for the soil layers subjected to the base acceleration for both linear and non-linear conditions. From the free field time history of the absolute acceleration the response spectrum of absolute acceleration at the free field is obtained by the usual procedure.

NUMERICAL STUDY

As illustrative example, the proposed method is applied in determination of seismic hazard curve and risk consistent response spectrum for Bhaktapur City, a typical location of the Kathmandu Valley. The 8 identified active faults in the vicinity of Bhaktapur City are considered as the earthquake sources for the study. Since the dimensions of the City are not large, the seismic hazard curve and the risk-consistent response spectrum at the bedrock level do not significantly vary across the length and breadth of the City, hence these quantities are computed for the center of the City. The important parameters for the calculation of the seismic hazard curve are shown in Table 1.

Table 1: Seismic Parameters of the Earthquake Sources (Faults)

#	Active Faults	Source-to-site Distance (km)	Mean Annual Rate, ν_i	Value of Coefficients		Probability Density Function of Magnitude				
				α	β	M5	M6	M7	M8	M9
1	MCT- 3.3	34.51	5.012	14.279	2.073	0.7365	0.0927	0.0117	0.0015	0.0002
2	HFF-1.13	53.33	1.585	11.976	2.303	0.7304	0.0720	0.0073	0.0007	0.0001
3	LH-4.10	60.12	5.012	14.279	2.073	0.7394	0.0931	0.0117	0.0015	0.0002
4	MBT- 2.5	66.66	1.585	11.976	2.303	0.7293	0.0729	0.0073	0.0007	0.0001
5	MBT- 2.4	95.55	1.585	11.976	2.303	0.7304	0.0730	0.0073	0.0007	0.0001
6	MBT- 2.6	142.22	1.585	11.976	2.303	0.7384	0.0728	0.0073	0.0007	0.0001
7	MBT- 2.3	180.15	1.585	11.976	2.303	0.7288	0.0729	0.0073	0.0007	0.0001
8	MBT- 2.7	230.09	1.585	11.976	2.303	0.7288	0.0729	0.0073	0.0007	0.0001

The values of *a* and *b* representing the seismicity of the sources are converted into α and β parameters to express the earthquake magnitudes in exponential distribution. The average rate of threshold magnitude exceedence for each of the potential earthquake sources is given, based on equation (3), by the following:

$$\nu_i = \exp(\alpha_i - \beta_i m_o) \quad \text{.................................} \quad (10)$$

in which, $\alpha = 2.303a$ and $\beta = 2.303b$, and $m_o =$ the lower threshold magnitude of earthquake which is set to 4.5 in the study.

The resulting probability distribution of magnitude in terms of the PDF is given by equation (4). In the absence of attenuation law developed for the region due to scanty earthquake data, 24 various existing empirical attenuation relationships are used for calculation of the seismic intensity in terms of PGA at the bedrock level of Bhaktapur City. These 24 empirical attenuation laws, as described by Douglas [11], are by: 1. Taleb; 2. Donovan and Bornstein; 3. Donovan; 4. Esteva and Rosenblueth; 5. Davenport; 6. Merz and Cornell; 7. Cornell, Banon and Shakal; 8. Battis; 9. Fukushima and Tanara; 10. Ambresseys and Bommer; 11. Tento, Franceschina and Marcellini; 12. McGuire; 13. Orphal and Lahoud; 14. Milne and Davenport; 15. Mickey; 16. Ohashi; 17. Joyner and Boore; 18. Sabetta and Pugliese; 19. Esteva and Villaverde; 20. Campbell; 21. Abrahamson and Litchiser; 22. Theodulidin and Papazachos; 23. Peng, Wu and Song (a); and 24. Peng, Wu and Song (b). The seismic hazard curve for the centre of Bhaktapur City using the exponential function for PDF for earthquake magnitude, and adopting 24 attenuation laws as described above, is shown in Fig. 2

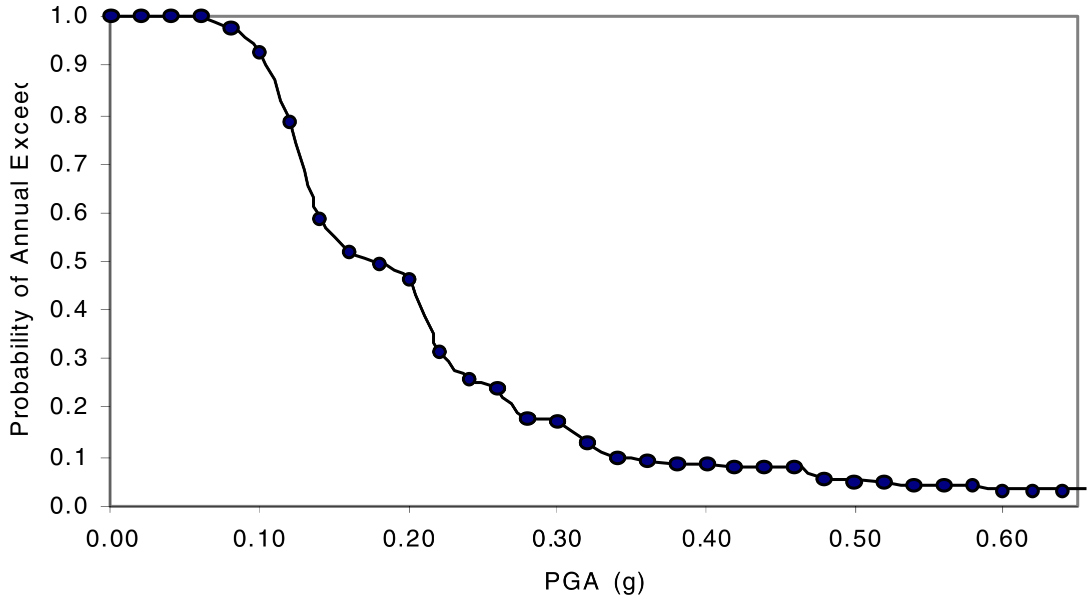

Figure 2. Seismic Hazard Curve for the Center of Bhaktapur City at the Bedrock Level

The normalized risk consistent response spectrum (spectral shape) is obtained for this site using the empirical relationship between the magnitude of earthquake and the response spectrum ordinates given by equation (5). The values for coefficients a(T), b(T) and c(T) in the equation are taken from Takemura et al. [6] and are shown in Fig. 1. Thus obtained risk consistent spectral shape for the center of Bhaktapur City at the bedrock level is shown in Fig 3.

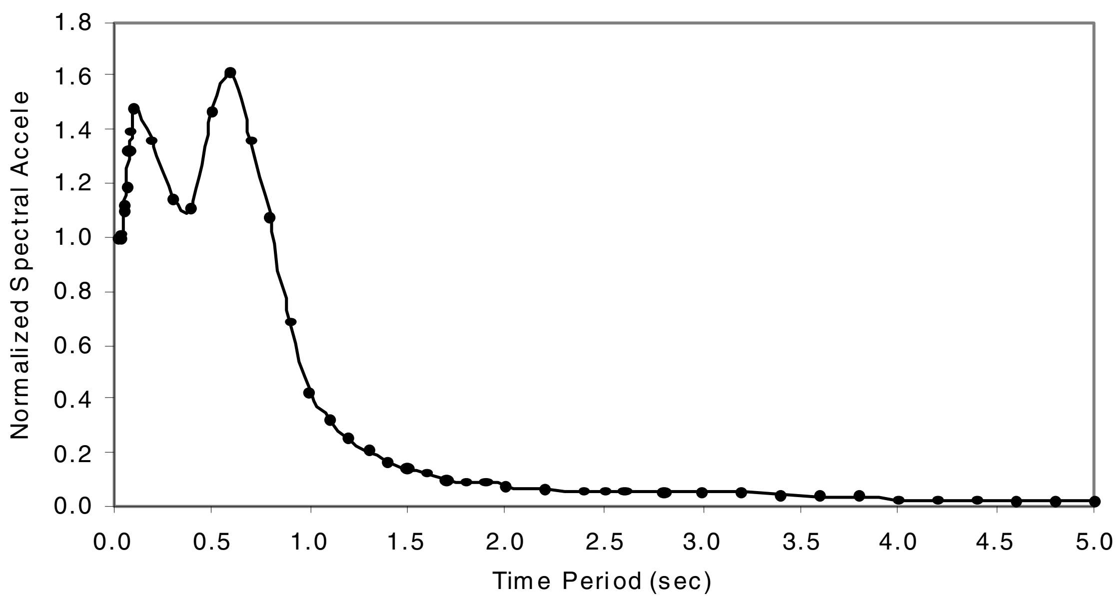

Figure 3. Risk Consistent Response Spectrum for the Center of Bhaktapur City at the Bedrock Level

Since the soil properties of Bhaktapur City vary across its length and breadth, for modification of the hazard curve and the spectral shape due to soil characteristics, three different sites with their soil profiles are considered. The majority of the soil layers are either clay or sandy clay. In order to obtain the hazard curve and the spectral shape at the top of the each of the three sites, the risk consistent time history of ground acceleration at the bedrock level is generated. The time histories of the free field ground accelerations are obtained by carrying out site response analysis with one-dimensional wave propagation analysis for both linear and non-linear soil behaviors.

The PGA amplification for the 3 sites, when soil behavior is assumed to be linear, is shown in Table 2. Evidently the PGA amplification substantially differs from one site to the other.

Table 2: PGA Amplification for 3 Typical Sites (Linear)

Site No.	Location	PGA Amplification
1	Durbar Square, Khauma	2.67
2	Taumadhi Square	2.10
3	Salan Ganesh Square	1.92

When these PGA amplifications are considered the hazard curves for the free field become different for the three sites. A typical hazard curve at the free field of the Site No.1 (Durbar Square, Khauma) is shown in Fig. 4. The hazard curve at the bedrock level is also shown in the same figure. The figure indicates that the hazard curve for the free field provides significantly greater probabilities of exceedence of PGA values.

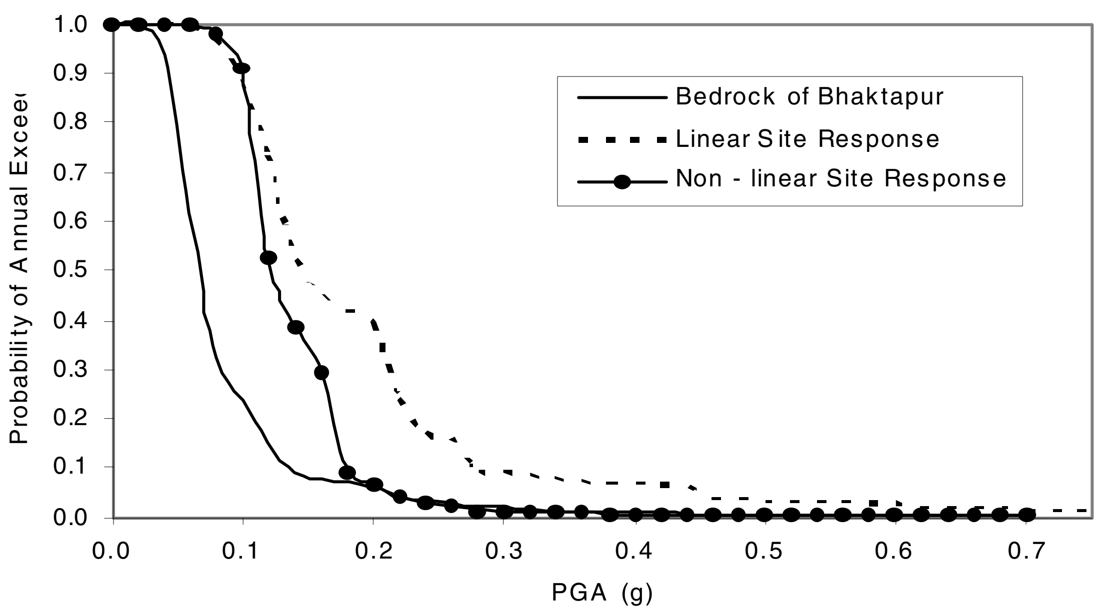

Figure 4. Typical Seismic Hazard Curve (Free field and at the Bedrock Level) at Site No. 1 Durbar Square, Khauma

The PGA amplification for 2 sites for different levels of PGA values when nonlinear behavior of the soil is taken into consideration is presented in Table 3.

Table 3: PGA Amplification for 2 Typical Sites (Nonlinear)

PGA at Bedrock Level	Sites	
	Site No. 1	Site No. 3
	Durbar Square, Khauma	Salan Ganesh Square
0.03g	2.40	2.02
0.08g	1.87	1.89
0.13g	1.28	1.23
0.18g	1.03	1.12
0.23g	1.02	1.11
0.28g	0.87	0.97

It may be seen from the table that the PGA amplification decreases with the increase in the input PGA value. It is because the nonlinear effect becomes more for higher level of excitation resulting in more dissipation of energy within the soil mass. For higher values of PGA (0.28g), the free field PGA may be deamplified (amplification less than one). Note that the PGA amplification is independent of the PGA level at the bedrock for linear behavior of the soil and is much greater than that for nonlinear soil behavior for higher values of bedrock PGA. Thus, consideration of actual soil behavior in the determination of the free field ground motion is extremely important, especially for higher levels of PGA at the bedrock level. The effect of the nonlinear soil behavior on the free field hazard curve is shown in Fig. 4 in which the hazard curves for linear and nonlinear soil behavior are compared. It is seen that the probability of exceedence is more for linear soil behavior and difference between the two increases for higher values of PGA.

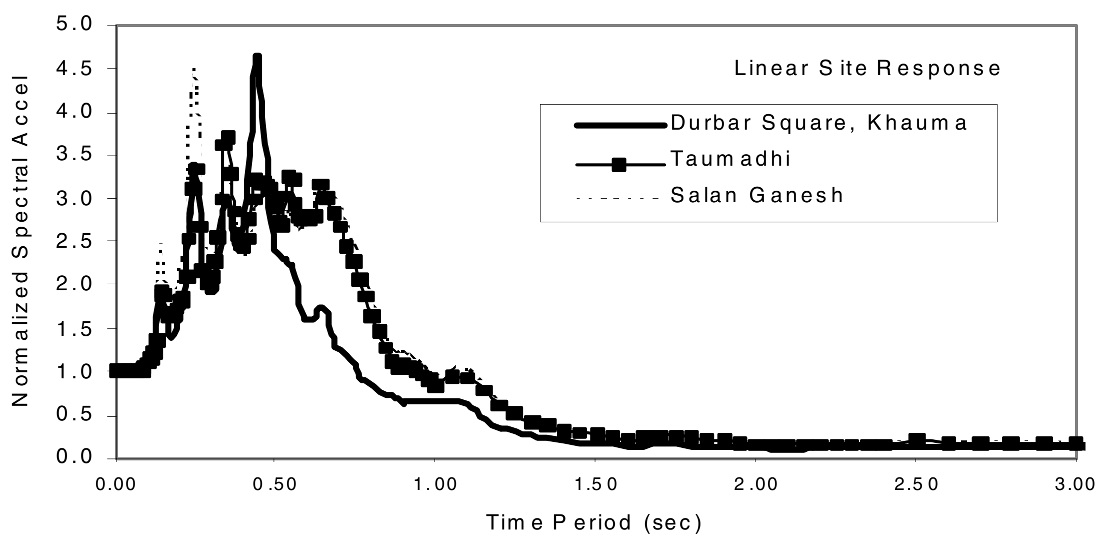

Figure 5. Normalized Risk Consistent Response Spectrum for Free Field Absolute Acceleration at Three Sites of Bhaktapur City (Linear Site Response)

The spectral shapes for the three sites are shown in Fig. 5, when linear behavior of the soil is considered. It indicates that the shapes of the risk consistent response spectrum can be significantly different from one site to the other, even though the input bedrock spectral shape remains the same. Comparison of Fig. 3 and Fig. 5 shows that the peak of the risk consistent spectrum at the free field may be significantly deviated from that at the bedrock level. This clearly shows that the input excitation to the structures may be significantly influenced by the soil conditions.

The risk consistent spectral shapes for a PGA level 0.23g for the same three sites, when nonlinear behavior of soil is considered, are presented in Fig. 6. It is again observed that the spectral shapes may significantly differ from one site to the other. Comparison of figures 5 and 6 shows that the spectral coordinates are drastically reduced near the peaks when nonlinear soil behavior is taken into consideration.

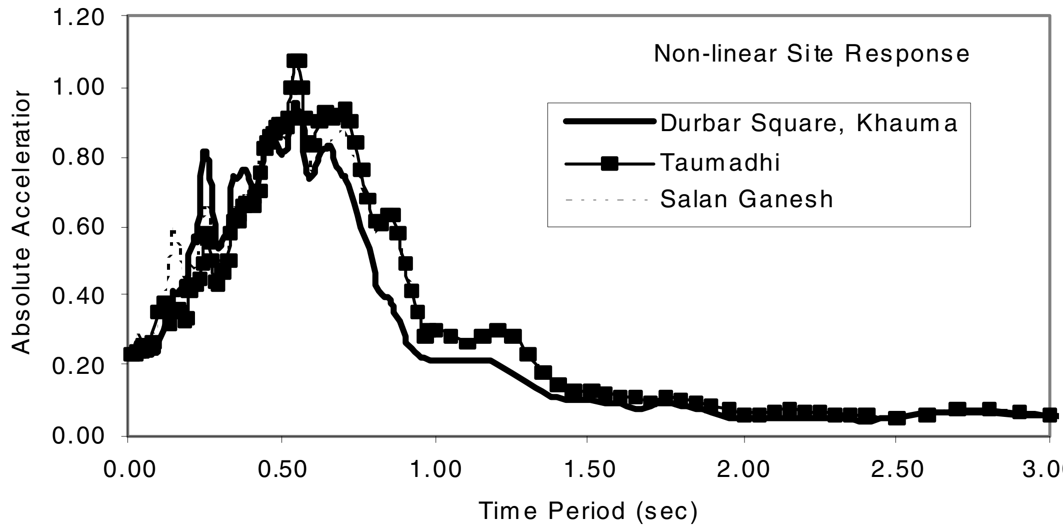

Figure 6. Normalized Risk Consistent Response Spectrum for Free Field Absolute Acceleration at Three Sites of Bhaktapur City for PGA at Bedrock = 0.23g (Nonlinear Site Response)

CONCLUSION

A simplified procedure is presented for obtaining hazard curve and risk consistent response spectrum for seismically vulnerable regions which do not have enough recorded data. The method takes help of the available attenuation laws and empirical formulae, which relates the response spectrum ordinates with the magnitude of earthquakes. The seismic risk is incorporated by using conditional probability of occurrence of PGA for a particular magnitude of earthquake, derived from the set of available attenuation laws. The hazard curves and the response spectra for the free field are obtained after duly considering the effect of overlying soil layer. Both linear and nonlinear soil behaviors are considered. The methodology is illustrated by obtaining hazard curves and risk consistent response spectra for three different sites of Bhaktapur City surrounded by eight earthquake sources. The results of the study lead to the following conclusions:

The hazard curves at the bedrock level and at the free field are different. The degree of difference depends upon the soil condition.

When the soil non-linearity is considered, the probability of exceedence of a PGA level denoted by the hazard curve is reduced; the reduction is more for higher levels of PGA.

The PGA amplification is much less for the nonlinear soil condition and may even become less than one. The risk consistent normalized acceleration response spectrum at the bedrock level of the Bhaktapur City is relatively broad banded.

The spectral shapes at the free field are significantly modified due to the soil effect.

The spectral shapes become broader banded when nonlinear behavior of soil is taken into consideration in comparison to those corresponding to linear soil behavior.

Modification in spectral shapes due to non-linearity depends upon the PGA level at the bedrock. For higher levels of PGA, the effect of non-linearity is more, the spectral shape becomes more broad-banded, and more reduction of spectral ordinates takes place near the peak.

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