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EFFECT OF LINEAR SOIL CONDITION ON SEISMIC INPUTS

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Abstract

Seismic inputs to structures in terms of risk consistent response spectrum and seismic hazard curves are developed at bedrock level considering ten independent seismic source zone in the vicinity of the Kathmandu valley. The seismic hazard curve is derived by assuming temporal occurrence of earthquakes to follow Poisson model. Response spectrum is developed using an empirical relationship of spectral ordinates with magnitude of earthquakes and epicentral distance. The seismic risk factor is introduced in response spectrum using conditional probabilities. Power spectral density function consistent with response spectrum is derived and ground acceleration time histories are derived from power spectral density function using Monte Carlo technique. To obtain free field hazard curves and ground motion parameters, one dimensional wave propagation analysis is used for two different underlying soil conditions.

Keywords

Hazard curve, Monte Carlo Technique, Power spectral density function, Risk consistent response spectrum

Introduction

Kathmandu valley is one of the most seismically active regions in the world. The valley is surrounded by numerous active faults, contributing to its high seismic risk. Seismic hazard potential of the valley can be evaluated using seismic hazard curves and peak ground acceleration (PGA) dependent spectral shapes on the surface of the bed rock. Although the seismic source may be same, ground motion parameters vary from site to site as the underlying soil condition can be different from one place to other.

Takemura *et al*.,(1989) provided a method for seismic hazard analysis using seismic hazard curves and PGA dependent response spectral shapes. Maskey and Datta (2004) developed free field seismic hazard curve and risk consistent response spectral shapes using both linear and nonlinear soil property in three different location of Bhaktapur city. Maskey (2005) studied different site-dependent earthquake ground motion parameters like acceleration time histories, power spectral density functions (PSDF) and response spectra in a probabilistic format, using both linear and nonlinear soil properties. Owing to the seismic risk of the valley, not many studies have been conducted to investigate the effects of different underlying soil condition on the seismic hazard evaluation of the valley.

Seismic Hazard Curve

Assuming Poisson model for annual occurrence of earthquakes, seismic hazard curve representing relation between seismic parameter (PGA) and its annual probability of exceedance P(A ≥ a) is proposed by Der Kiureghian and Ang (1977) as,

$$P\left(A \geq a\right) = 1 - \exp\{-v\left(A \geq a\right)\} \quad (1)$$

where, v(A ≥ a)is the annual occurrence rate of PGA 'A' exceeding a specified value 'a' and given as following expression,

$$v(A \geq a) = \sum_k v_k \sum_j \sum_i P_k\left(A \geq a | m_i, r_j\right) P_k\left(m_i\right) P_k\left(r_j\right) \quad (2)$$

where, $P_k\left(m_i\right)$ *and* $P_k\left(r_j\right)$ represents the probability mass function of magnitude and epicentral distance at the k-th zone respectively. $P_k\left(A \geq a | m_i, r_j\right)$ is the conditional probability of PGA, 'A' exceeding 'a' for a given 'm_i' and 'r_j'. 'v_k' represents the annual occurrence rate of earthquake for the k-th source.

A recurrence relationship which gives the average rate at which an earthquake of particular size will be exceeded, is used to characterize the seismicity of source zone. The standard Gutenberg- Richter recurrence law can be used as:

$$\lambda_m = 10^{a-bm} = \exp(\alpha - \beta m)$$

where α =2.303a β = 2.303b (3)

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

$$P_M\left(m\right) = \frac{\beta \exp\left[-\beta\left(m - m_0\right)\right]}{1 - \exp\left[-\beta\left(m_{maxm} - m_0\right)\right]} \quad (4)$$

where, m_0 is the lower threshold magnitude of earthquake, m_{maxm} is upper threshold maximum magnitude and m is magnitude of the earthquake.

Attenuation law used to obtain the ground motion parameter, such as PGA for a given magnitude of earthquake and site to source distance is taken from Shiuly (2018), as

$$\text{Log (PGA)} = -2.0709 + 0.4028m - 0.9707\log R - 0.0008R; \quad \sigma_{loga} = 0.16 \quad (5)$$

PGA is in g units, 'm' and 'R' are earthquake magnitude and source epicentral distance in Km respectively.

Risk Consistent Response Spectrum

Risk consistent spectral shape at bedrock level is developed by empirical relationship between magnitude M, epicentral distance R and time period T with normalized response spectrum ordinates (normalized by its maximum acceleration value) S_N(T) which is given by Takemura *et al.*, (1989)

$$S_N^* = \ln S_N\left(T\right) = a\left(T\right)M - b\left(T\right)lnR + c\left(T\right) \quad (6)$$

in which a(T), b(T), c(T) are constants for a particular value of period (T). These constants are taken from Takemura *et al.*, (1989) as shown in Fig. 1.

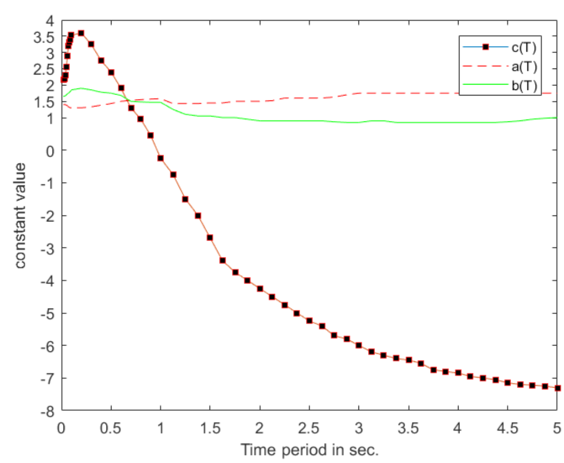

Figure 1. Variation of constants with time period

The conditional mean value of natural logarithm of response spectrum for the k[th] point source given that PGA is between $a_1 \, and \, a_2$ is obtained as,

$$\bar{S}^*_{N\ j}(T) = \sum_i S^*_N(m_i, T) P_k(m_i | a_1 < A \le a_2) \quad (7)$$

The conditional probability $P_k(m_i | a_1 < A \le a_2)$ can be calculated using Bayes theorem as

$$P_k(m_i | a_1 < A \le a_2) = \frac{P_k(a_1 < A \le a_2 | m_i) P_k(m_i)}{P_k(a_1 < A \le a_2)} \quad (8)$$

Considering all seismic sources, the conditional mean value of $\bar{S}^*_{N\ k}(T)$ is expressed by

$$\bar{S}^*_N(T) = \frac{\sum_k \bar{S}^*_{Nk}(T) \nu_k P_k(a_1 < A \le a_2)}{\sum_k \nu_k P_k(a_1 < A \le a_2)} \quad (9)$$

Similarly, the conditional mean square value $\bar{S}^{*2}_N(T)$ can be obtained by replacing the mean value by mean square value in equation (7). Then, the conditional standard deviation is given by,

$$\sigma\{S^*_N(T)\} = \sqrt{\{S^*_N(T)\}^2 - \bar{S}^{*2}_N(T)} \quad (10)$$

The plot of $\bar{S}^*_N(T)$ vs T gives the mean response spectrum and plot of $\bar{S}^*_N(T) + \sigma\{S^*_N(T)\}$] vs T provides 84th percentile response spectrum.

Effect of Soil Conditions on Response Spectrum and Hazard Curve

Empirical relationship used for obtaining the response spectral shapes and PGA at the site are valid for the bedrock level. So, effect of the soil condition above the bedrock level should be considered. Frequency domain spectral analysis is carried out for the ground response analysis in which the PSDF of the ground motion $S_b(\omega)$ at bedrock is related to PSDF of free field ground motion, $S_g(\omega)$ as,

$$S_g(\omega) = S_b(\omega) |A(\omega)|^2 \quad (11)$$

where, $A(\omega)$ is transfer function of soil and is obtained from one dimensional wave propagation analysis given by Kramer (1996) as,

$$A(\omega) = 1 / \sqrt{\cos^2(\omega H / V_s) + [\zeta \omega H / V_s]^2} \quad (12)$$

in which H is the thickness of uniform soil layer; V_s is the shear wave velocity and ζ is the percentage of critical damping of soil.

PSDF of ground acceleration is related to its corresponding response spectrum using relationship derived by Der Kiuregwan and Neuenhofer (1992)

as,

$$S_b(\omega) = \frac{\omega^{\theta+2}}{\omega^\theta + \omega_f^\theta} \left[\frac{2\xi\omega}{\pi} + \frac{4}{\pi\tau} \right] \left[\frac{D_j(\omega, \xi)}{p_s(\omega)_0} \right]^2 \quad (13)$$

where ω is frequency in rad/sec; $S_b(\omega)$ is PSDF of ground acceleration; τ is duration of earthquake shaking and taken as 15 sec; ω_f and θ are two constants that can be obtained by an iteration procedure and as suggested by Der Kiuregwan and Neuenhofer (1992), is taken as 0.705 and 3 respectively; $p_s(\omega)_0$ is peak factor for the response to white noise; $D_j(\omega, \xi)$ is the displacement response spectrum ordinate for damping ratio ξ and period T=2π / ω.

Peak factor of the response as suggested by Vanmarcke (1976), is used here and is given as,

$$P_f = \sqrt{(2 \ln\{2n[1 - exp - (\delta_e \sqrt{\pi \ln(2n)})]\})} \quad (14)$$

where,

$$n = \left(\frac{\Omega\tau}{2\pi}\right)(-\ln r_c)^{-1}; \Omega = \sqrt{\frac{\lambda_2}{\lambda_0}}$$

$$\delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}} \quad (15)$$

r_c is confidence level taken as 95%; δ is a measure of the spread of frequency content of response PSDF about central frequency; $\delta_e = \delta^{1.2}$; λ_0, λ_1 and λ_2 are first three response spectral moments and is obtained as,

$$\lambda_n = \int_0^{\omega_n} \omega^n S(\omega)\, d\omega;\ n = 0,1,2 \qquad (16)$$

ω_n is cutoff frequency beyond which contribution of frequency is negligible in PSDF.

The mean peak value of the absolute free field acceleration i.e. PGA at ground surface can be obtained from three moments of its corresponding PSDF as,

$$(PGA)_f = \sqrt{\lambda_0}\, P_f \qquad (17)$$

where λ_0 is first spectral moment and is calculated by area under PSDF of absolute acceleration of free field. Square root of λ_0 gives the root mean square value of response PSDF. P_f is peak factor of the response calculate using equation (14) and (16).

To obtain hazard curve at free field, the conditional probability in equation (2) is modified by considering free field PGA and annual exceedance probability of PGA is changed accordingly.

Once the absolute free field acceleration PSDF is obtained, the ground acceleration time history consistent with the PSDF can be derived using *Monte Carlo Simulation* technique given in Yang (1985). From thus obtained time history of absolute acceleration, the response spectrum of free field absolute acceleration compatible with generated time history can be derived using definition of pseudo acceleration response spectrum.

Numerical Study

Ten independent seismic point sources in the vicinity of Kathmandu valley has been identified. Characteristics of seismic sources and source to site distances are given in table 1. The mean annual occurrence rate of earthquake of magnitude larger than the threshold magnitude (m_0=4.5) was calculated for each source using given 'a' and 'b' parameter value and then the result was divided by 16. For each source of earthquake, ten earthquake magnitude intervals have been selected. Probability that magnitude will be within an interval between lower bound and upper bound is calculated by using equation (4). Depth of overlying soil is assumed to be 20m with 5% of critical damping of soil. Two type of soil condition have been considered as soft soil with shear wave velocity V_s = 80m/sec and stiffer soil with V_s = 200m/sec.

Table 1 Characteristics of seismic sources and source to site distance

Source Zone	Eq. Sources (Faults)	M maxm	a- value	b- value	Source to site distance (km)	Mean annual rate of occurrence(vi)
1	HFF-1.10	6.5	4.17	1	83	0.02923
2	HFF-1.15	6.8	3.38	1	84	0.00474
3	MBT-2.3	7	4.24	1	140	0.03435
4	MBT-2.4	6.7	4.17	1	78	0.02923
5	MBT-2.5	6.9	4.17	1	38	0.02923
6	MCT-3.3	7	4.17	1	21	0.00806
7	HFF-1.13	6.7	4.17	1	47	0.02923
8	LH-4.10	6.5	4.17	1	68	0.00806
9	MBT-2.6	7.3	4.23	1	104	0.03356
10	LH-4.7	7.1	4.24	1	185	0.00947

Response Spectrum at Bed Rock Level

Normalized acceleration response spectrum at bedrock level for different PGA interval is shown in Fig. 2. It is seen that shape of response spectrum is not significantly affected by PGA intervals. PSDF consistent with response spectrum, for PGA value of 0.23g at bed rock level is shown in Fig. 3. A sample time history of acceleration synthesized from the PSDF is given in Fig. 4 whose PGA is nearly equal to 0.23g.

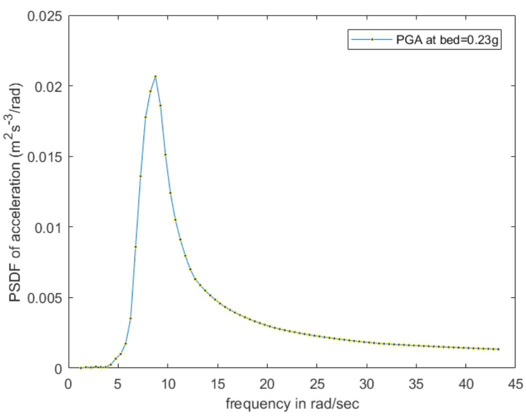

Figure 2 Risk consistent response spectrum at bed level for various PGA interval

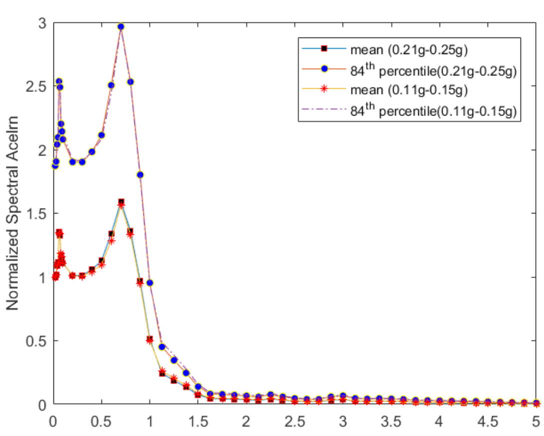

Figure 3 Risk Consistent PSDF at bedrock for 0.23 PGA

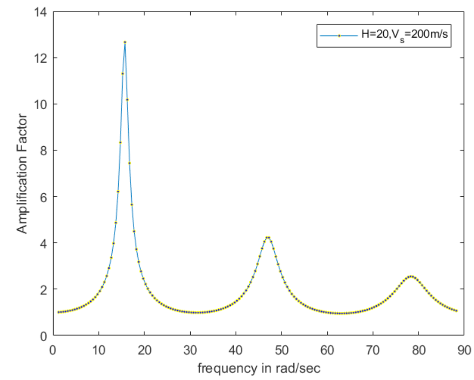

Figure 4 Simulated time history from bedrock PSDF (PGA=0.23g)

Effect of Soil Condition on Absolute Free Field Response Spectra

Fig. 5 shows the transfer function of overlying soil layer of V_s=200m/s. It is seen from the figure that for stiffer soil (V_s=200m/s), the first peak of transfer function occurs at the fundamental frequency of the soil ($\pi V_s/2H$). Fig. 6 shows the PSDF of absolute free field acceleration response spectra for stiff soil (V_s=200m/s) and its corresponding time history is shown in Fig. 7. Free field response spectral shapes are shown in Fig. 8 and Fig. 9 for soil condition of V_s=200m/s and V_s = 80m/s respectively. It is seen that ordinate of PSDF and response spectra shape is high near their corresponding fundamental frequency of underlying soil.

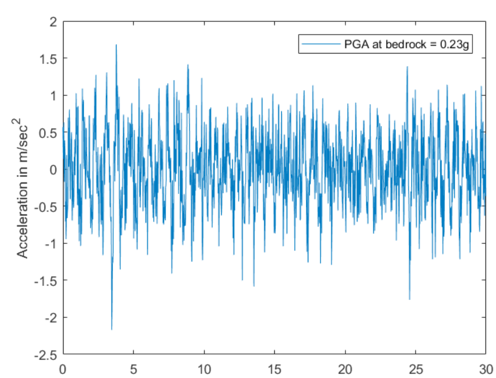

Figure 5 Transfer function of soil V_s=200m/s

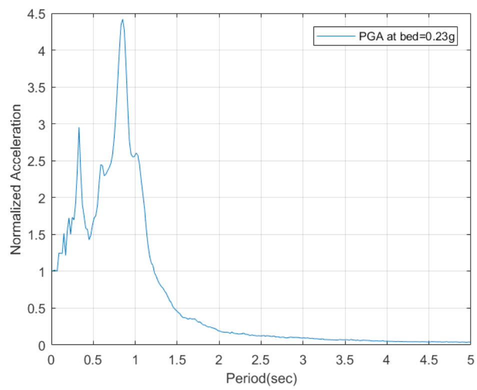

Figure 6 Free field PSDF for soil V_s =200m/s

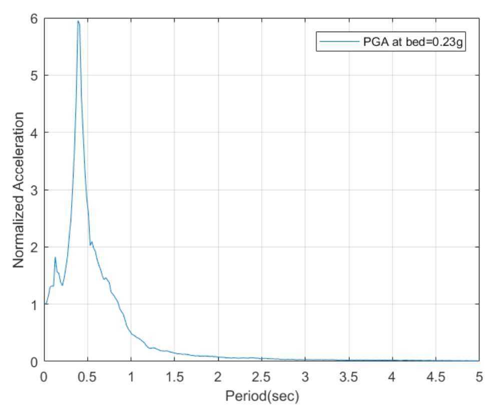

Figure 7 Simulated time history from free field PSDF (V_s =200m/s)

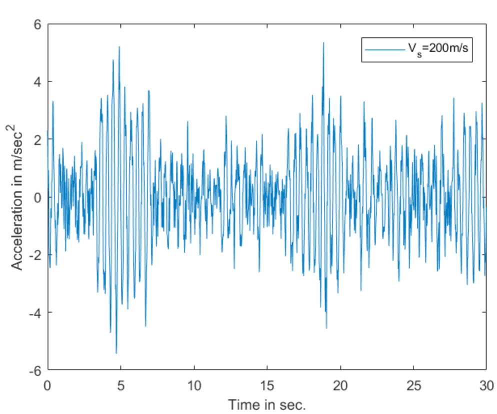

Figure 8 Normalized risk consistent free field response spectrum for V_s =200m/s

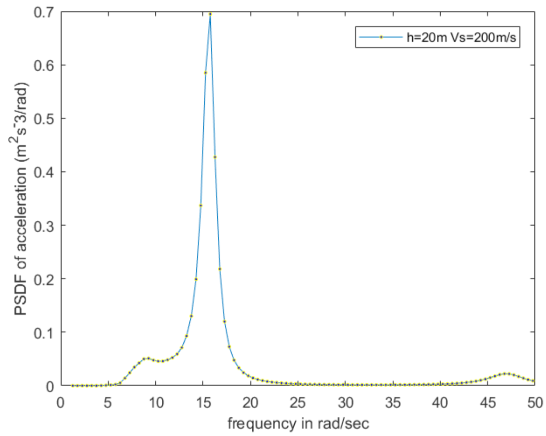

Figure 9 Normalized risk consistent free field response spectrum for V_s =80m/s

Frequency of Content of Time Histories

Using Fast Fourier Transform (FFT) algorithm, Fourier amplitude spectrum of synthesized time histories at bed rock and free field condition (Vs=200m/s) is shown in Fig. 10 and Fig. 11. As expected, it is seen that the ordinate of Fourier spectrum is large at the frequency band where respective PSDF ordinate has peaked.

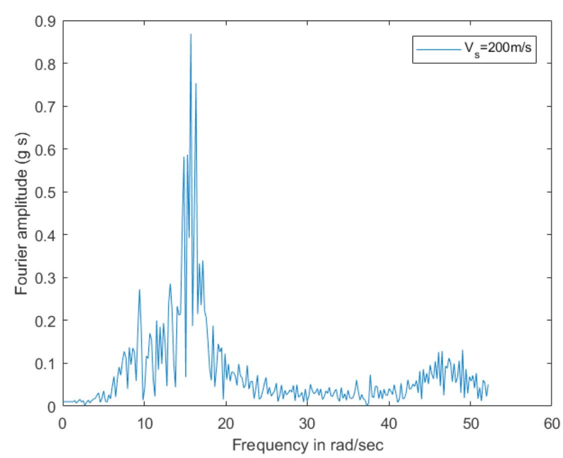

Figure 10 Fourier amplitude spectrum of acceleration time history at bedrock (PGA=0.23g)

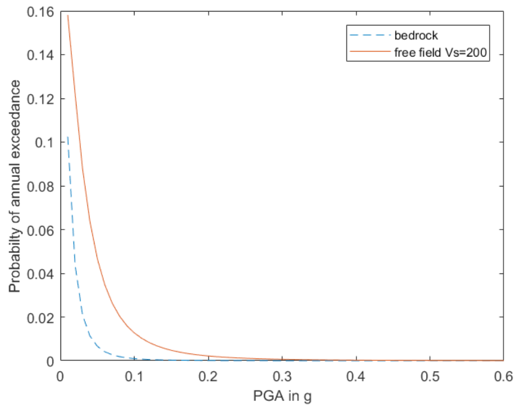

Figure 11 Fourier amplitude spectrum of acceleration time history at free field (V_s =200m/s)

Effect of Soil Condition on Hazard Curve

Fig. 12 compares the hazard curve for bed rock level and free field hazard curve. PGA amplification for each soil condition is given in table 2. It is seen from the hazard curve that probability of exceedance of PGA is more when effect of soil condition is considered.

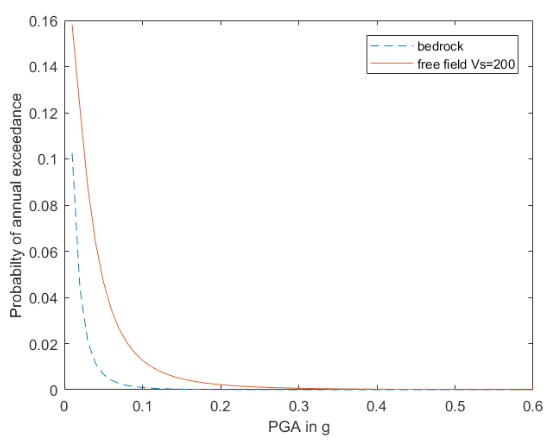

Figure 12 Seismic hazard curve for bedrock and free field level (V_s=200m/s)

Table 2 PGA amplification of different types of soil

Shear Wave velocity (m/sec)	PGA Amplification
V_s=80	1.87
V_s=200	2.62

Conclusion

A procedure of seismic hazard analysis for obtaining seismic hazard curve and risk consistent response spectrum of seismically active region with limited earthquake record data is presented. Hazard curve is developed assuming occurrence of earthquake as Poisson model. The risk consistent response spectrum is obtained using empirical relationship which relates spectral ordinates to earthquake magnitude and epicentral distance. The seismic risk factor is included in normalized response spectrum by using conditional probability, which describes the probability of occurrence of certain magnitude of earthquake given that PGA lies between two limits. Free field hazard curves and response spectrum are developed considering one dimensional wave propagation analysis. Ground acceleration time histories is simulated and their characteristics are investigated. The Methodology is illustrated by taking ten seismic sources in the vicinity of the Kathmandu valley and following Conclusion can be drawn:

1. Shape of response spectrum is insensitive to PGA intervals considered in the study.
2. The shape of response spectrum at free field are significantly modified when soil amplification effect is considered. The spectral ordinate is maximum near the first natural frequency of the underlying soil.

3. For linear soil condition PGA amplification is less for soft soil than stiffer soil. For soft soil (V_s=80m/s) and stiffer soil (V_s =200m/s) PGA amplification was found to be 1.87 and 2.62 respectively.
4. Probability of exceedance of PGA values in hazard curves is more when the effect of underlying soil is considered. For stiffer soil the exceedance probability is more than the soft soil.

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