Sensitivity Analysis of SHAKE based Soil Site Response Modelling

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ABSTRACT: Determining and verifying the limitations of commercially available programs for analyzing ground response are important, because inaccurate results will affect the inputs to the design response spectra of structures and thus inputs to building codes and the disaster mitigation process.

Shake2000 is a Windows based computer program that is a variant of SHAKE which is one of the earliest and most successful computer codes that calculates the ground response. Although Shake2000 has been widely used for many years, there are not enough studies that reveal the usage limitations of SHAKE

Shake2000 was used for the ground response analysis of Lalitpur, Nepal. A synthetic strong motion was used in the analysis for the worst case scenario; M=8, D=48km (hypocentral), a_{max}=0.48g and resulted in maximum values of PGA=1.54g, and SA=2.799g for 3Hz frequency. For M=6.7, D=6.4km (epicentral), a_{max} =0.5g record, maximum values were PGA=3.44g and SA=8.64g for 2Hz frequency.

Although the reason for such high SA values could have been the use of stiff, thick soils and very severe earthquakes, further research revealed that when large magnitude earthquakes with high accelerations and stiff soils were simulated, SA values obtained were not reliability, such as 8.64g. In this study, it is demonstrated that the certainty of Shake2000 decreases when used with stiff soils and records with a_{max} of 0.48 g and above.

1 INTRODUCTION

It is widely accepted that, unlike firm bedrock, soil deposits can significantly amplify ground motion. Therefore, understanding of the soil site response is crucial, because many urban settlements are located on soil deposits.

Ground response analyses are used to predict ground surface motions, to develop design response spectra, to evaluate dynamic stresses and strains for evaluation of liquefaction hazards, and to determine the earthquake-induced forces that can lead to instability of earth and earth-retaining structures (Kramer, 1996). For soil site analysis by numerical methods, one-dimensional equivalent-linear models or advanced ones can be used. Overall, it appears that one-dimensional, equivalent-linear analysis has become the *de facto* standard for site response prediction in North American practice (Kramer and Paulsen, 2004).

For soil site analysis, various computer codes are commercially available. SHAKE is one of the earliest and most widely-used computer codes that calculates one-dimensional (1D), equivalent-linear response for horizontally layered sites. Shake2000 (Ordonez 2002) is a Windows-based code, inheriting its roots from SHAKE (Schnabel et al. 1972), as are others such as, Shake Edit, Shake91, EduShake and PROSHAKE, which are common codes that are used not only in scientific research but also in private sector projects. It is important to describe the limitations and reliability of these codes, because inaccurate results could result in unexpected damage to structures in case of an earthquake and thus in poor disaster mitigation planning. Although there are many reports that have used SHAKE for their soil site analysis, there are not enough studies that address the usage limitations of the computer code.

Shake2000 was used for seismic microzonation of Lalitpur, Nepal where there is high to very high seismic hazard (Zhang et al. 1992-1999). Lalitpur is a sub-metropolitan city with an area of 15km^2 in the Kathmandu valley, including lake deposits up to 424m depth. Scenario earthquake records were chosen to target the worst case scenario, represented by using, large magnitudes and short distances. The parameters such as Peak Ground Acceleration (PGA) and 5% damped Response Spectral Accelerations (SA) were calculated via Shake2000, from which we have realized that in many cases, the parameter values were amplified more than expected. Thus, this paper tries to reveal the limitations and sensitivity of SHAKE in cases of large magnitude earthquakes with high maximum accelerations (a_{max}) and stiff and deep soil conditions.

2 BACKGROUND AND METHODS

Data collected from the literature, including previous studies in the Kathmandu region and field surveys, were not sufficient to support an empirical approach for the soil site analysis in Lalitpur. Thus we have implemented 1D equivalent-linear modelling.

In the 1D modelling, local earthquake recordings would represent the expected ground motions best, therefore their availability was investigated from existing online databases, the literature and the academic community in Nepal. Some earthquake records were obtained from the Department of Mines and Geology (DMG) of Lalitpur, but they were lacking earthquake magnitude, distance, and location information. In the end, enough information could not be gathered from these recordings and thus importing them into SHAKE was not beneficial. Because of the unavailability of local input motions, the approach was to use the existing database in SHAKE which has more than 2500 records. Input motion selection procedure from this vast database was based on discussions with Nepalese geologists, seismologists, other scientists who worked in this region and the literature (Giardini 1999; Bajracharya, personal communication, 2003).

Generally, input motions are selected to satisfy appropriate magnitude and distance parameters. Corresponding to the 1934, Bihar, Nepal earthquake (Mw=8.1, R=48km), a scenario earthquake recording with a magnitude of 8 and a 10 km epicentral distance was estimated as the worst case scenario for the region (personal communication Jean-Paul Avouac, 2003). A more probable scenario was considered to be the same magnitude but with a 50 km distance. Consequently, the first record chosen was a record developed by MAE (Mid-America Earthquake Center) named RR 2B (MAE) that satisfied this more probable case, with a magnitude of 8, hypocentral distance of 48 km and a_{max} of 0.48g (Ordonez 2002). The second scenario was estimated to have a magnitude of 7, and approximately 10-15 km distance. This second record was chosen as a simulated Los Angeles (LA) earthquake record with 7.1 magnitude, 17.5km epicentral distance and a_{max} of 1.19g (Ordonez 2002). The third record was from the SAC project (Ordonez 2002), the Northridge (SAC) record with 6.7 magnitude, near-field 6.4km epicentral distance and a_{max} of 0.50g. All records were inserted as outcropping in the analysis.

There were 14 boreholes; 7 shallow (1.45m-60m) and 7 deep (136m-350m), in the study area. Though 1D modeling would benefit from specific geotechnical information from the boreholes, the number of the boreholes was not sufficient to model the area to output microzonation maps using spatial interpolation techniques in a Geographical Information Systems (GIS) environment. Also, other information types such as geophysical investigations were not available from the fieldwork or the literature. On the other hand, a generalized subsurface geology model with X and Y coordinates and depth values was available. This generalized geology was interpolated to a four-layer model and was used as the basis of the soil modeling (Piya 2004). The four layers were recent alluvial, lake, pre-lake deposits and bedrock respectively. The first layer from the surface consisted mainly of sandy and silty sediments, and the second layer consisted of clay sediments. The third layer consisted mainly of gravel. The fourth layer was bedrock, which consisted mainly of limestone, sandstone, slates and phyllites. The unit weight (UW; γ) and shear-wave velocity (Vs) values were based on general values which were derived from different information sources (Koloski and Schwarz 1989; Whitlow 1995) and discussions with Seifko Slob and Robert Hack in 2003. The estimated values were: recent alluvial layer with γ =17.5kN/m^3 and Vs=450m/s, lake deposits with γ =16kN/m^3 and Vs=600m/s, pre-lake deposits with γ =20kN/m^3 and Vs=1700m/s and bedrock with γ =22kN/m^3 and Vs=3000m/s.

The damping ratio curves used in this study are the curve of Lysmer et al.(1971) and Schnabel et al. (1971) for sand, the curve of Schnabel et al (1972) for clay, the curve of Seed et al. (1986) for gravels, and the curve of Schnabel (1973) for rock. The shear modulus reduction curves used were the curve of Sun and Seed (1988) for sand with CP=1-3 KSC, the curve of Sun and Seed (1988) for clay with plasticity index (PI) =20-40, the curve of Seed et al. (1986) for gravels and the curve of Schnabel (1973) for rock.

Vs values for modelling the borehole profiles were grouped into two sets. The first set consisted of the minimum values, where Vs_{Clay}=300m/s, Vs_{Sand}=600m/s, $Vs_{Gravels}$=1700m/s, and Vs_{Rock}=3000m/s. The second set consisted of the maximum values, where, Vs_{Clay}=600m/s, Vs_{Sand}=1200m/s, $Vs_{Gravels}$=1700m/s, and Vs_{Rock}=3000m/s.

2.1 *Methodology 1*

This methodology used two models; A & B. In model A, geotechnical information from borehole logs was used with the three records chosen. In model B, the four-layer soil profile with the geotechnical information and the three scenario earthquakes were used. For both models we have calculated PGA and SA values for 5% damping using SHAKE. The two models were then compared in terms of those outputs.

2.2 *Methodology 2*

This methodology used the four-layer soil profile and the MAE earthquake record to create PGA, MMI, 5 % damped response spectral accelerations for several frequencies and characteristic site period maps. The four-layer model was used to create a grid map within the GIS environment using the Integrated Land and Water Information System (ILWIS) software (Koolhoven et al. 1988). A 500m by 500m pixel size was used for the Lalitpur grid, which resulted in 60 pixels in total. For each pixel we ran SHAKE using the soil profile provided and the thickness read from the thickness maps. After converting to raster, the PGA map was been bilinearly densified and bicubically resampled. To convert PGA values to MMI Scale, Eq. 1 was used (Trifunac and Brandy, 1975).

$$MMI = (1/0.3)*(LOG_{10} (PGA*980)-0.014) \qquad (1)$$

The tabular data was associated with PGA, and then MMI values were generated. Four maps were created for the chosen fundamental frequencies; 1, 2, 3 & 5Hz roughly corresponding to the natural frequencies of 10, 5, 3 and 2 storey buildings respectively (Day 2001). The corresponding 5% damped response spectral accelerations were obtained from the computed response spectra.

2.3 *Sensitivity Analysis*

A sensitivity analysis was applied to some of the input parameters of the SHAKE model, i.e.: shear wave velocity (Vs), unit weight (γ), and soil thickness (H). Different scenario earthquake records were used as input as well to determine their effect on the soil response. The earthquake record was selected as Adak, Alaska; 1971, M=8 and R=67km with a_{max}=0.22g. Sensitivity analysis was applied following the 1D modeling, in which large variations in PGA and SA were observed and this record was chosen to have less variation using a lower a_{max} value. Two sets of soil profiles were created: one with two layers, sand and rock; and one with three layers, sand, clay and rock. The two-layered soil profile used sand with H=12m, γ =17kN/m^3, Vs=600m/s, and shear modulus reduction curves and damping of sand as given above. For rock, properties were as given above. The clay layer was with H=24m, γ =16kN/m^3, Vs=300m/s, and other properties for clay as given earlier.

3 RESULTS

In methodology 1, PGA and SA values calculated from the two models, four-layered model and the borehole log profiles are compared in Table 1. The maximum PGA (3.14g) value was obtained from C40 borehole which has the same location as Point 10 (PGA $_{max}$=3.44g) in the four-layer model. PGA values for borehole SPT 6 and SPT 25 were the same, with 2.38g as the highest value. Borehole B25 which has the same location as Point 8 on the four-layer model has a SA value of 8.64g at 2Hz frequency for the LA earthquake record. Because the SA value of borehole B25 is very high, we list some SA at different frequencies in Table 2 and show the response spectra in Figure 1. The soil profile of borehole B25 consisted of clay layer (with H=106m, γ=16kN/m^3 and Vs=300m/s), clay layer with gravels (with H=6.1m, γ =16kN/m^3 and Vs=300m/s), gravel layer (with H=22.55m, γ=20kN/m^3 and Vs=1000m/s) and rock layer (with γ=22kN/m^3 and Vs=3000m/s).The maximum SA values for the five frequencies mapped (0.3 Hz, 1 Hz, 2 Hz, 3 Hz and 5Hz) for Borehole B25 was 1.94g at 1Hz frequency and for Point 8 was 4.28g for 3Hz for the MAE earthquake record.

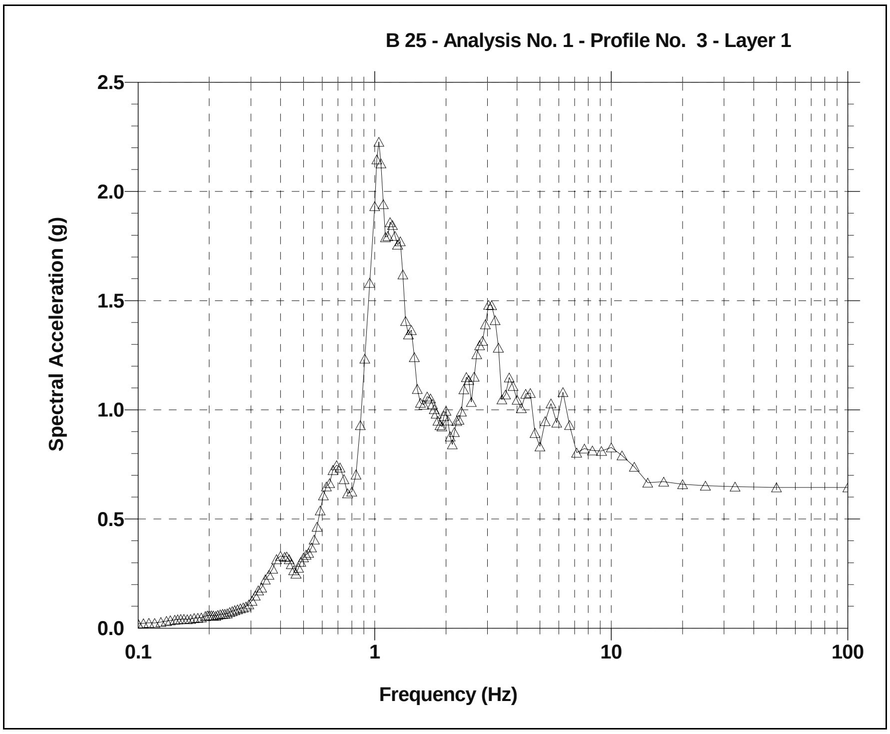
In methodology 2, calculated PGA values for the MAE record were between 0.56g and 1.40g for the study area. SA values for 1, 2, 3 and 5Hz frequency were between 1.1-4.9g, 1.4-3.4g, 1.0-3.6g and 0.7-3.0g respectively shown in Figure 2. The MMI map showed two dominant intensities; 9 and 10, where MMI 10 values clustered on the northwest for MAE scenario earthquake record. In addition, an MMI map was also produced using another simulated earthquake record; New Madrid with M= 7.1, D=65km and a_{max} =0.18g for which computed MMI intensities were between 9 and 11. The New Madrid earthquake record also produced high values on the northwest side of the city of Lalitpur, but SA values were lower, values ranging from 0.1g to 1.24g, and clustering was more spatially scattered compared with the other records. Data shows that for a given record large variations in the PGA and SA values can be obtained (Figure 2), also wide spread of PGA response values can be gathered for different records for the same soil profile as shown earlier in Table 2.

Table 1 : PGA values calculated for scenario earthquakes with minimum (1) and maximum (2) Vs value sets for the four-layer model and the borehole logs.

Earthquake	**Four layer model with Vs - Set 1**		**Borehole log profile with Vs - Set 1**	
	PGA in g (min)	**PGA in g (max)**	**PGA in g (min)**	**PGA in g (max)**
MAE	0.17	0.70	0.11	1.10
LA	0.32	1.59	0.23	3.15
SAC	0.29	1.07	0.17	1.19
	Four layer model with Vs- Set 2		**Borehole log profile with Vs - Set 2**	
	PGA in g (min)	**PGA in g (max)**	**PGA in g (min)**	**PGA in g (max)**
MAE	0.48	1.42	0.35	1.54
LA	1.00	3.44	0.54	2.38
SAC	0.80	1.77	0.39	2.16

Table 2 : SA values at 5 frequencies for the three scenario earthquakes at B25 borehole and the corresponding point 8 of the four-layer model

B25 borehole log			
Frequency_ (Hz)	***MAE Scenario_SA (g)***	***LA Scenario_SA (g)***	***SAC Scenario_SA (g)***
0.3	0.12	0.5	0.88
1	1.94	1.65	1.02
2	0.98	1.18	0.71
3	1.48	0.88	0.95
5	0.81	0.59	0.62
Point 8 of four-layer model (same location as B25)			
Frequency _Hz	***MAE Scenario_SA (g)***	***LA Scenario_SA (g)***	***SAC Scenario_SA (g)***
0.3	0.14	0.26	0.32
1	0.65	2.61	1.05
2	2.60	8.64	3.62
3	4.28	5.48	5.03
5	1.62	3.40	2.18



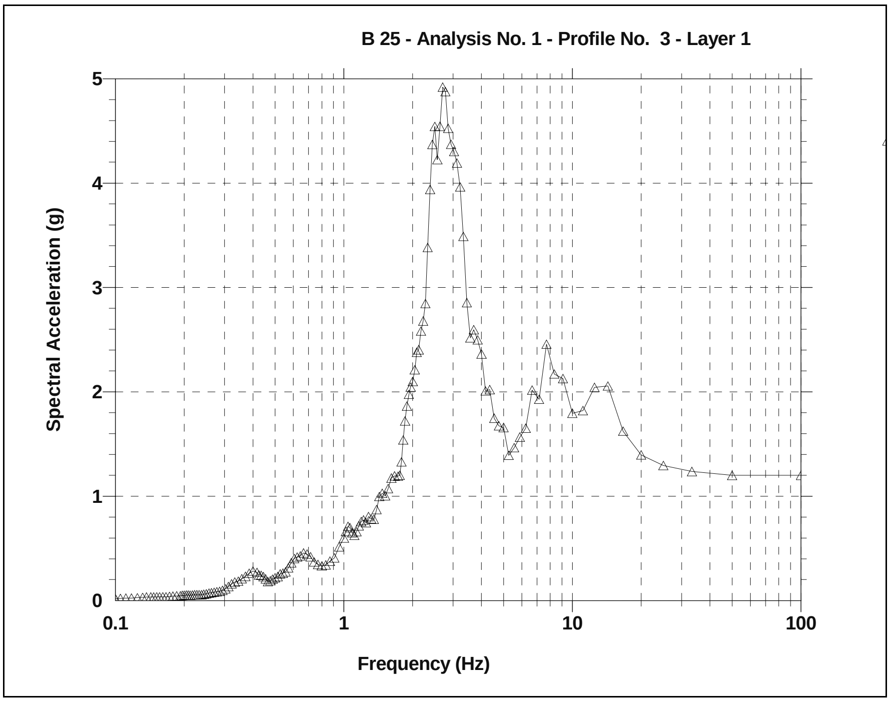
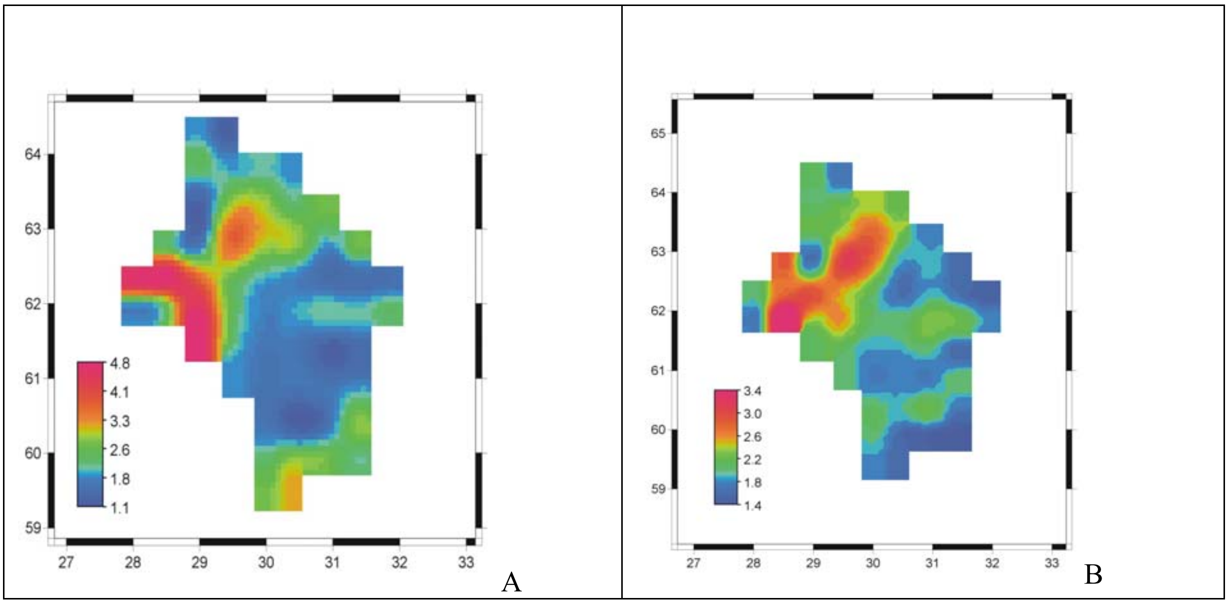


Figure 1 : Response spectrum for (A) borehole B25 and (B) the corresponding Point 8 of the four-layer soil profile for the MAE record (M=8; R=48km and a_{max}=0.48g).



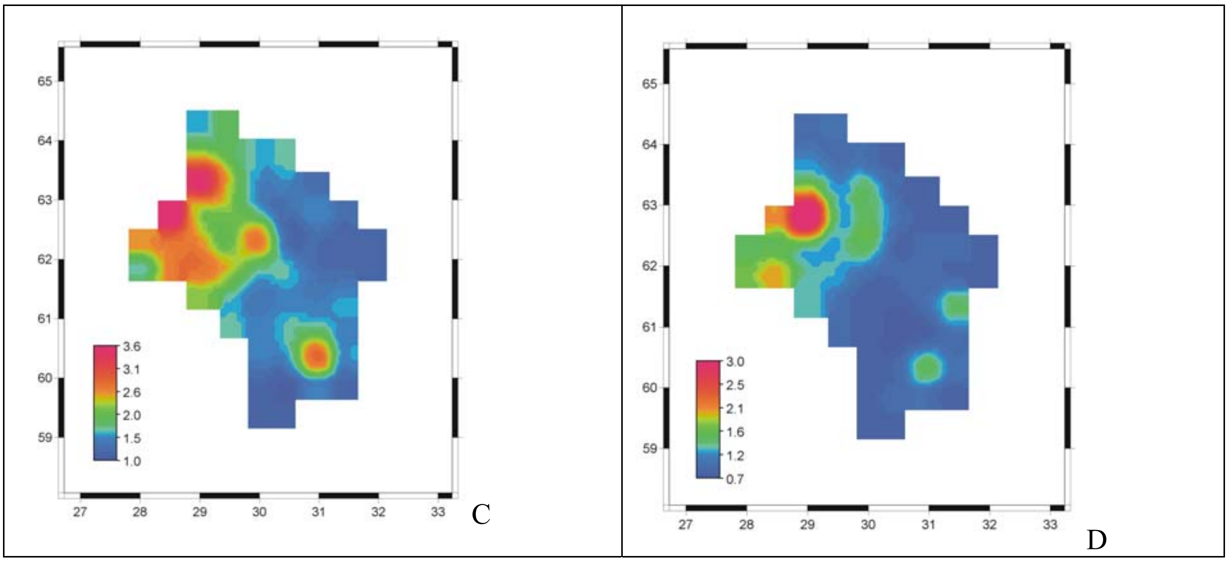


Figure 2: 5% damped response spectrum accelerations throughout Lalitpur, Nepal for the MAE Center earthquake record input (M=8; R=48km and a_{max}=0.48g) for frequencies of (A) 1 Hz, (B) 2 Hz, (C) 3 Hz and (D) 5 Hz using the four-layer model.

In sensitivity analysis, input motions (MAE, LA and SAC) produced PGA values for the four-layer model between 0.52g to 3.44g as shown Table 2. Shear-wave velocity produced 20% PGA value change, for values between 30m/s and 1219m/s for the three-layered model and 34% change between 30m/s and 3005m/s for the two-layered model. Data shows after 808m/s, Vs increase has very low effect on PGA values for two layer model. Soil thickness sensitivity analysis showed a 10% change in PGA values between 2m and 100m for the three-layer model and 23% change in the two-layer model between 10m and 40m. For unit weight, values between 15kN/m^3 and 22kN/m^3, PGA values changed 2% for the three-layer model and did not show any change in the two-layer model.

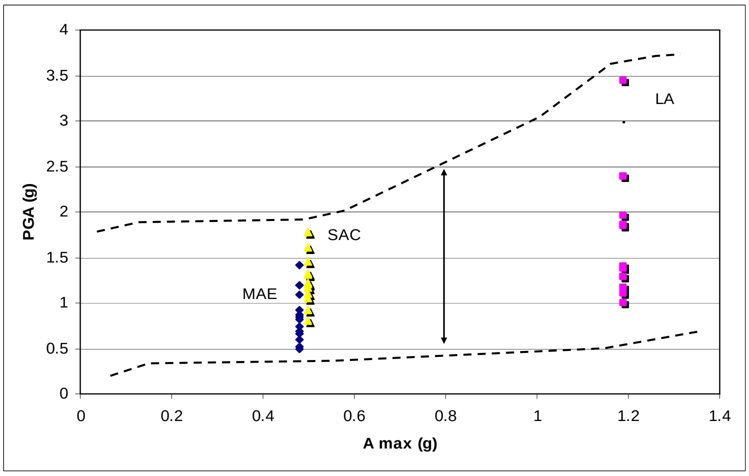


Figure 3: Graph showing the PGA values that are obtained for the 3 different earthquakes from sensitivity analysis results (MAE (diamonds), LA (squares) and SAC (triangles).

4 DISCUSSION AND CONCLUSIONS

In order to select an appropriate soil-site modeling and the appropriate computer code, we used SHAKE for soil site analysis in Lalitpur, Nepal, which is the *defacto* for 1D equivalent linear analysis and is popularly applied for soil sites where large magnitude earthquakes are expected (Kramer and Paulsen 2004). Several considerations have been taken into account while choosing this computer code. First, the subsurface geology was mostly horizontally layered, which was suitable for 1D horizontally layered equivalent linear modeling. Second, geotechnical information from the boreholes was mainly available for the input requirements of SHAKE. Third, local earthquake recording data was lacking, but SHAKE enabled the selection of suitable records from its earthquake database.

Using the available literature and experts' knowledge, three scenario earthquake records were selected; MAE, LA and SAC from SHAKE's database. All three earthquakes resulted in high PGA values (PGA_{LA}=3.44g at maximum) and very high SA values (SA_{LA}=8.64g for 2Hz frequency at maximum). Depending on these results, MMI intensity maps and response spectrum values were difficult to evaluate. Consequently, using SHAKE to derive further data for engineering practice such as design response spectrum analysis would not be favorable for the given initial results.

Kramer and Paulsen suggested that using an equivalent linear model may be computationally efficient and provide reasonable results when strains are small and accelerations are modest (Kramer and Paulsen 2004). Hence, the New Madrid earthquake record with a_{max} value of 0.18g was used as a complementary worst case scenario for the study area. This earthquake record and the four-layer model produced more realistic results, such as a highest PGA of 2.10g and a highest SA of 1.24g at 3 Hz frequency on the response spectrum. The MMI map for the New Madrid input scenario also corresponds to the JICA study, where the highest MMI values were clustered on the northwest side of the city (JICA 2002). Additionally, the Adak earthquake scenario was used in sensitivity analysis with an a_{max} of 0.063g, which generated 0.36g as the maximum PGA value. From the results obtained, maps were generated for MM intensity and 5% damped response spectral accelerations for several frequencies which could be beneficial for use in further engineering studies.

Similar studies performed using SHAKE and high PGA and/or SA values are repeated in the literature (Chen and Johnson. 1983; Lo Presti et al 2006; Marcial 2005). Nevertheless, the limitations of SHAKE are not fully explored. In this study it is shown that if stiff and deep soils with large magnitudes and high a_{max}; (a_{max}>=0.48g) values are to be simulated; the computer code SHAKE is not the right model to use for response analysis. The a_{max} value of 0.48g corresponds to the MAE record that has the lowest a_{max} earthquake record value which was used in this study and produced high/very high PGA/SA values. The a_{max} =0.48g value also corresponds to the maximum recommended median relationship for use in empirical correlations in soft soil site amplification curve where the curve reaches its threshold around 0.5g PGA value at rock (Cameron and Green, 2004). Although some of the results that we have obtained may be artifacts, we conclusively showed high PGA values and very high SA values for the 1D equivalent linear analysis. At this point, we suggest that it is important to revisit the generated outcomes that were obtained under the same conditions. The potential causes of the high PGA and very high SA values may be related to nonlinear behavior of the soil. In a very recent study, Rodriguez-Marek and Bray, 2006 reported that seismic site-response analyses for soft soil sites require a fully nonlinear model to capture the important effect of soil failure during the earthquake shaking. Though 1D equivalent linear modeling tries to address the nonlinearity with iterative use of linear solutions and by adjusting values of modulus and damping until they are compatible with computed levels of strain (Kausel and Roesset 1984), fully nonlinear response is not sufficiently represented in 1D linear modeling where the input motion probably causes higher shear strains than the estimate of the 1D equivalent linear model (Ching and Galser 2001).

Another crucial point for soil site modeling is sensitivity analysis which is generally applied. In this study, sensitivity analysis was also applied because parameters such as SA values can be difficult to evaluate and also have a significant impact on predicted ground motion results (Kramer and Paulsen 2004). The results showed that the important parameters that have impact on PGA values were: input motion and shear-wave velocity, thickness and unit weight of soils, in order of importance. This study also provides additional evidence for Sigbjornsson's study for the uncertainty analysis of strong ground motion and similarly, input motion had the highest sensitivity factor (Sigbjornsson 2004). In this study, all the parameters except unit weight showed complex behavior. Therefore, further sensitivity/uncertainty analysis is required to better understand the behavior of the parameters; probabilistic Monte Carlo analysis could be used for advanced analysis. Particularly it is important for the input motion since its sensitivity is the highest.

In summary, although there are studies that highlight the over-estimation of amplification of the analysis for 1D equivalent-linear modeling (Kausel and Roesset 1984; Kramer and Paulsen 2004), there are not enough studies that address the limitations of the method. In this study it is demonstrated that for a SHAKE based approach, a critical part of the definition of the input scenario earthquake record is not only the magnitude and distance, but also the a_{max} parameter. The technique seems reliable when used with a_{max} values lower then 0.48g for stiff and deep soil sites. Over this limit, advanced methods; such as 2D and/or 3D modeling where, basin effects can be incorporated should be considered. Particularly, nonlinear approach using computer codes such as ONDA (Lo Presti et al 2006), should also be taken into consideration.

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