MONTE CARLO SIMULATIONS OF SOIL AMPLIFICATION FUNCTIONS FOR SITE-SPECIFIC SEISMIC HAZARD ANALYSIS – CASE STUDY: TEHRAN, THE CAPITAL CITY OF IRAN

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ABSTRACT

To design earthquake resistant buildings and structures, strong ground motions' accelerations and their uncertainties should be estimated. Nevertheless, the effect of soil-profile amplification needs to be evaluated for a complete site-specific seismic hazard estimation. Despite all uncertainties in hazard analyses phases including source, magnitude and attenuation equations, soil profiles are of high deviations in properties and characteristics in a study area. To tackle soil profile uncertainties in the site-specific seismic hazard estimation results, in the present work, a Monte Carlo simulation (MCS) approach has been proposed and examined to evaluate soil amplification function at each soil profile location or borehole. In the proposed approach, shear modulus, damping ratio, soil density and layer thickness are considered as random variables, which follow their corresponding probability distribution functions. The method includes 10,000 times randomising soil layer thicknesses as well as shear modulus reduction models, damping increase models and unit weights for each soil profile. In the present paper, soil amplification functions are achieved utilising SHAKE91 while an in-house subroutine generates a mega-input file for MCS at each soil profile. Furthermore, greater Tehran, the capital city of Iran and one of the most seismically active urban areas in the world, has been considered as a case study for the proposed method. Analysing the soil borehole data received from the governmental authorities, MC simulated mean soil amplification functions as well as the transformed surface uniform hazard spectrum from the bedrock spectrum have been presented respectively, for a borehole among all the database in Tehran area.

INTRODUCTION

In the earthquake engineering practice, the quantification of local site effects on the ground motion at the soil surface is of particular importance for earthquake resistant design (Lopez-Caballero and Modaressi-Farahmand-Razavi, 2010). The most important site effect is the amplification due to the impedance contrast and the frequency content filtering.

The energy released during an earthquake is represented by stress waves propagating through the bedrock and surfacing at the site of interest. In terms of the geotechnical characteristics of the site, the site is typically modelled as a series of horizontal layers with varying properties. In most cases, the site is represented by softer soils close to the surface and stiffer soils at depth. The increase in stiffness with depth is due to the older age of deeper material and the confining effect of the overburden.

The primary cause of amplification of earthquake motion is the decrease in velocity of seismic waves in soil deposits relative to the underlying bedrock. The decrease in velocity coupled with the conservation of energy leads to an increase in the amplitude of the ground shaking. Furthermore, the contrast between the soil layers and the underlying bedrock causes a series of reflections that generate upward and downward travelling waves. The interference of these waves modifies the ground shaking observed at any location (Robinson et al., 2006).

To simulate numerically one dimensional seismic soil response, two approaches can be considered. The equivalent-linear approach and a truly non-linear elasto-plastic modelling are the methods, which are being used for the soil amplification modelling and analysis. Equivalent linear ground response modelling is by far the most commonly utilized procedure in practice (Bardet et al., 2000). For the ground response analyses of the present paper, SHAKE91 (Idriss and Sun, 1992) has been utilized. The program computes the response of a semi-infinite horizontally layered soil deposit overlying a uniform rock half-space subjected to vertically propagating shear waves. The analysis is done in the frequency domain and for any set of properties it is a linear analysis. Consistent with the equivalent linear analysis, an iterative procedure is used to account for the nonlinear behavior of the soils.

Soils exhibit nonlinear behavior during shearing. It means that with increasing the shear strain, shear modulus of soil decreases. The relationship between shear modulus and strain amplitude is typically characterized by a normalized modulus reduction curve. The nonlinearity in the stress-strain relationship results in an increase in energy dissipation and, therefore, an increase in material damping ratio with increasing strain amplitude (Darendeli, 2001).

Furthermore, the soil profile and the corresponding properties (e.g. shear wave velocity, density, and shear modulus) exhibit some degrees of uncertainty. The uncertainties inherent in the soil profile parameters and the bedrock earthquake motion oblige the surface ground motion to become of high uncertainty as well. Thus, pure deterministic site effects analysis is not recommended in the design practice. In the present paper the soil amplification analysis is described and the Monte Carlo simulation is utilized in regard for the natural uncertainty of the surface ground motion and amplification functions.

Because the transfer function is defined as the ratio of the soil surface amplitude to the rock outcrop amplitude, the soil surface amplitude can be obtained as the product of the rock outcrop amplitude and the transfer function. Therefore, the response of the soil layer to a periodic input motion, can be obtained by the following steps,

- Expressing the input (rock outcrop) motion in the frequency domain using a Fourier series as the sum of a series of sine waves of different amplitudes, frequencies, and phase angles
- Calculating the transfer function
- Computing the Fourier series of the output (ground surface) motion as the product of the Fourier series of the input (bedrock) motion and the transfer function
- Expressing the output motion in the time domain by means of an inverse Fourier transform

RANDOM SOIL PROFILE MODELLING AND STOCHASTIC GROUND RESPONSE ANALYSES

To provide a rational reliability analysis of a geotechnical system, there is a need for realistic random soil models that can then be used to assess probabilities relating to the design (Fenton, 1999; Rota et al., 2011; Zhang et al., 2011). Soil properties of interest are shear modulus, fraction of critical damping, unit weight and thickness of layers modelled as random fields (Bergamo et al., 2011). The shear modulus is modelled using the lognormal distribution. This choice is motivated by the fact that this parameter is positive, and the lognormal distribution enables analyzing its large variability (Nour et al., 2003). The thickness of each type of textural layers is fitted with a lognormal distribution as well (Li et al., 1999; Rota et al., 2011).

After considering proper probability distribution functions for the soil parameters, the random fields for these parameters, required for the analysis, are generated using simulations by the Monte Carlo method (Badaoui et al., 2009; Li et al., 1999; Manolis, 2002; Rota et al., 2011). This method consists of performing a set of probabilistic realizations of the medium, used to predict the transfer function and the extreme acceleration at ground surface via deterministic calculations for each realization, and proceeding to the statistical treatment of the obtained results (Nour et al., 2003). The parameters are treated as random variables and given as input to a deterministic model, which propagates uncertainties in the solution by repeated calculations (Bazzurro and Cornell, 2004; Andrade and Borja, 2006; Nour et al., 2003).

In addition to the inherent uncertainty of soil parameters, the uncertainty of input motion in the soil amplification analysis can play an important role in the output motion variation range. Thus, the input motion selection is a sensitive part of analysis. The minimum number of real records, specified and indicated by Eurocode 8, is seven records. Real accelerograms are usually selected on the basis of proper geological and seismological constraints and the most important requisite is that in the records selection, the spectrum-compatibility is considered (Rota et al., 2011).

The predicted mean values and standard deviations of the shear modulus reduction curves and the damping increase curves accounting for the uncertainty in the values of model parameters and variability due to modeled uncertainty, presented by Darendeli, (2001), have been considered here as the required random variables for creating the MC simulated mega-input file for SHAKE91. Furthermore, Darendeli, (2001) considered a correlation matrix for the strain levels. The matrix contains the correlation coefficients of the values of standard deviation in different strain levels in the calibrated model. This predicted correlation structure between strain levels for shear modulus and damping curves of Darendeli, (2001) has been considered in the proposed modelling and simulations as well.

MONTE CARLO SIMULATIONS FOR SOIL AMPLIFICATION FUNCTIONS OF THE CENTRAL AREA OF TEHRAN CITY OF IRAN

The studied area mainly consists of sedimentary deposits of Quaternary era, which has been known as Tehran alluvial formation. Accordingly, the wet densities for gravelly, sandy and clayey soils are estimated using regression analysis (JICA, 2000). According to this information, a mean value equal to 2.1 (g/cm3) and a standard deviation equal to 0.1 (g/cm3) are adopted for the density of soil profile layers in the soil amplification analyses in the Tehran area. In addition, the relationship between SPT and strength of deposits for Tehran has been presented by Jafari et al. (2002). In the present study, according to Figure 1, the average values of mean and standard deviations of the existing relationships has been adopted (Taheri, 2012).

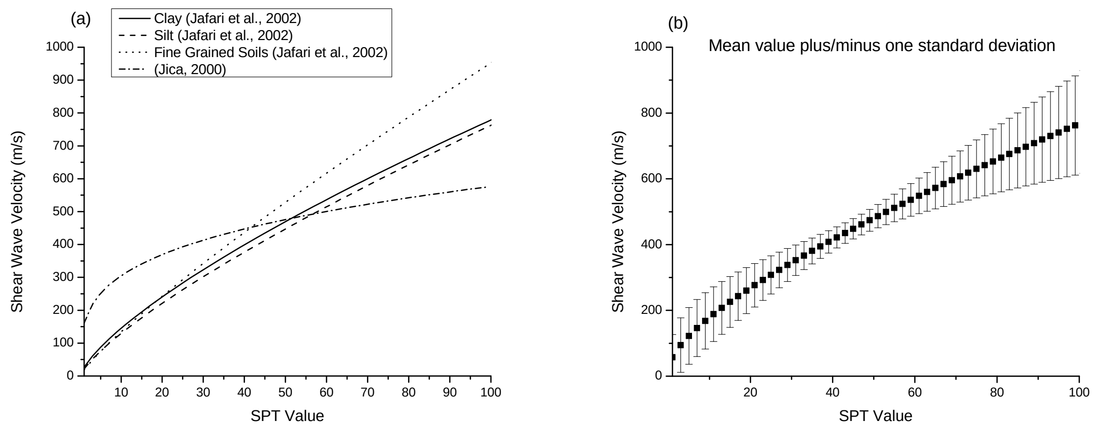

Figure 1.Relation between SPT blow counts and shear wave velocity of ground resulted from the geological site investigation of the Tehran area (after JICA, 2000; Jafari et al., 2002; Taheri, 2012)

For selecting the ground motion records for the ground response analysis at any borehole of interest, the uniform hazard spectrum (UHS) corresponding to the borehole geographical coordinates is computed. Ground motion acceleration records are selected herein study from NGA database of Pacific Earthquake Engineering Research Center (PEER) ground motion database. The record selection is conducted according to the spectrum-compatibility assumption. In this regard, the UHS of each borehole with 10% exceedance probability in 50 years is defined as the target spectrum (Table 1). In addition, the related scaled acceleration spectra compatible with the target UHS have been presented in Figure 2, accordingly. The borehole database, which is used in this study, has been provided by the Building and Housing Research Center (BHRC) of Iran. The database comprises more than 500 borehole logs, but the computations are presented for only one borehole here.

Table 1. Acceleration records selected for the soil amplification analyses at BH23 (borehole no.23) (each row in the table represents both fault normal and fault parallel records of the related station)

NGA#	MSE	Scale Factor	Event	Year	Station	Magnitude	Rrup(km)
946	0.05	4.6	Northridge-01	1994	Antelope Buttes	6.69	46.9
1021	0.07	3.2	Northridge-01	1994	Lake Hughes #4 - Camp Mend	6.69	31.7
59	0.10	13.1	San Fernando	1971	Cedar Springs- Allen Ranch	6.61	89.7
3251	0.10	5.6	Chi-Chi- Taiwan-05	1999	TTN042	6.2	85.2
2687	0.11	23.3	Chi-Chi- Taiwan-03	1999	TTN042	6.2	93.5
957	0.11	1.9	Northridge-01	1994	Burbank - Howard Rd.	6.69	16.9
1060	0.14	4.0	Northridge-01	1994	Rancho Cucamonga – Deer Can	6.69	80
143	0.18	0.3	Tabas- Iran	1978	Tabas	7.35	2

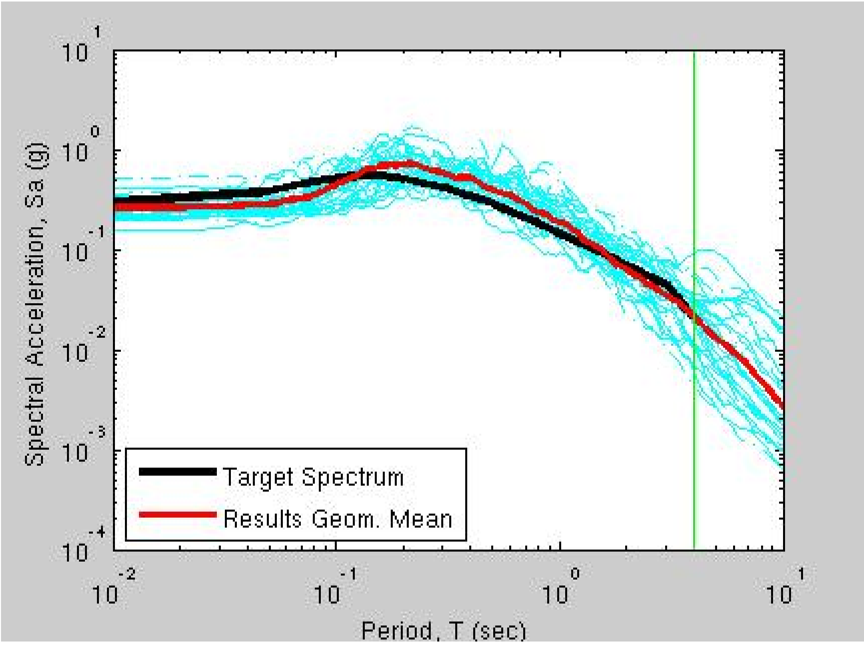

Figure 2. The scaled spectrum-compatible ground motion acceleration record selection for the soil amplification analyses. This figure is an output of the web-based PEER interactive application for the record searching and selection

In summary, all stages of randomization process and the Monte Carlo simulation for the ground response analysis for each borehole can be presented as follows.

1. Soil profile parameters' randomization, which includes shear wave velocity, unit weight and thickness of each layer in the soil profile. The randomization is conducted 1,000 times according to the MCS sample size. This sample size is selected in accord with the time and system limitations (see Figure 3).
2. Soil dynamic models' randomization in which shear modulus curve and damping curve are randomized in 1,000 times.
3. Input motion randomization. In this stage, for any random set of soil profile and dynamic behaviour curves, one of the 16 spectrum-compatible acceleration records for the under analysis borehole is randomly selected. In other words, each of 1,000 random runs is associated with a randomly selected motion from the pool.
4. Producing input files for the repetitive ground response analyses utilizing SHAKE91.
5. Conducting the ground response amplification analysis 1,000 times and extracting 1,000 amplification functions and the surface acceleration response spectra for the under study borehole (see Figure 4 and Figure 5).

An in-house program has been developed for producing SHAKE91 input files and repetitive analyses for 1,000 times (Taheri, 2012), during pre and post data processing. After performing the MC simulations and ground response analyses, a clear relationship between the maximum amplification factor in each amplification function and the natural period of vibration of the soil profile can be inspected. A comparison between the bedrock UHS as the target spectrum for acceleration record selecting and the mean and mean plus one standard deviation surficial response spectrum is depicted in Figure 6.

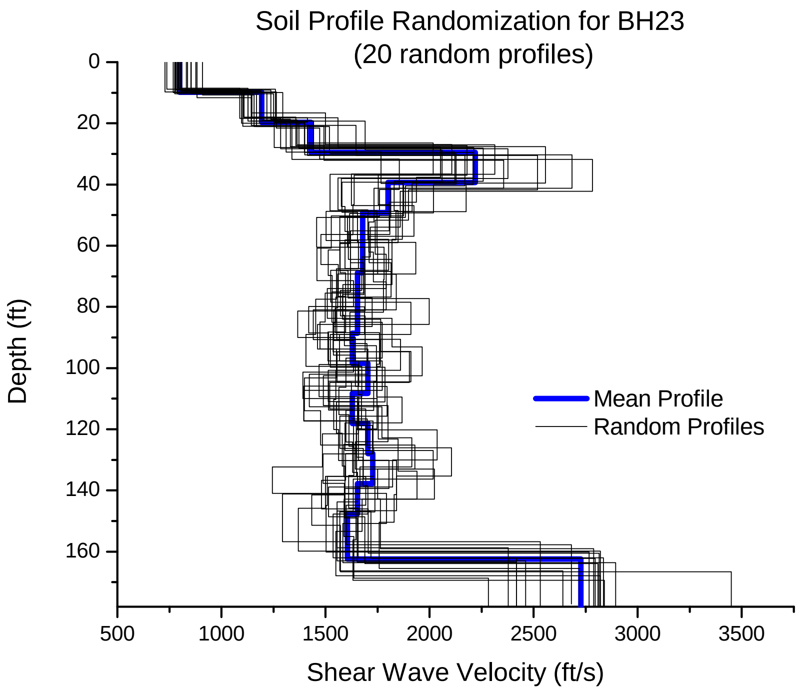

Figure 3. Demonstrative random soil profiles for BH23

CONCLUSIONS

Nevertheless, no matter how a seismic hazard analysis is precise and accurate, it cannot be completely reliable and realistic without regarding site effects and soil amplification factors. The most important site effect, which is the soil amplification due to the impedance contrast and the frequency content filtering, was investigated and evaluated in the city of Tehran utilizing Monte Carlo simulation technique to overcome the inherent uncertainties in the aforementioned analyses. To simulate numerically one-dimensional seismic soil response, the equivalent-linear approach was adopted and applied. SHAKE91 was selected for the ground response analysis in the Tehran area. Since the deterministic ground response analysis cannot represent the degree of uncertainty in the outputs of the soil amplification analysis, a Monte Carlo simulation with parameter randomizations and repetitive computations was applied for the outputs uncertainty inspection and determination. The results manifested that the peak amplification factors occur around the natural periods of vibration of soil profiles. These amplification factors can magnify the amplitudes of ground acceleration record in the frequency domain by several times. Therefore, a fully probabilistic consideration of amplification functions is recommended for the ground response analysis of the site-specific seismic hazard assessment to be utilized as the intensity measures for the performance-based design practices.

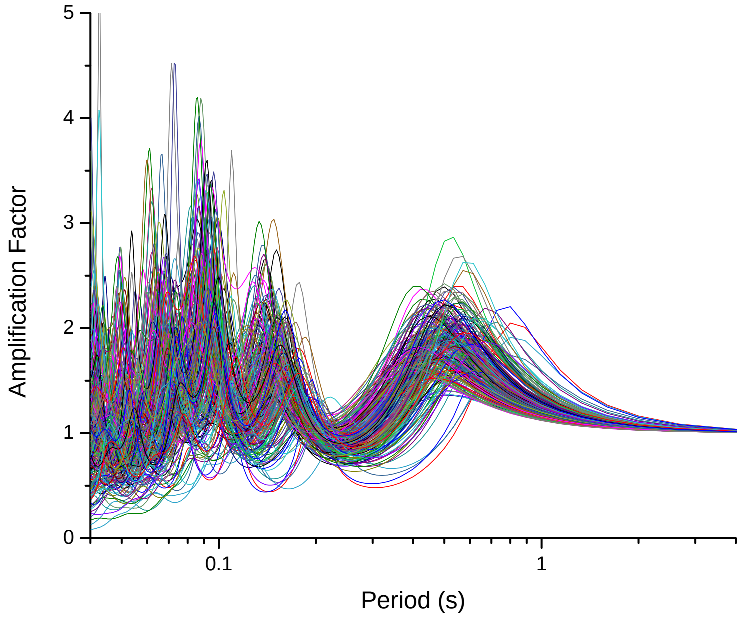

Figure 4. Amplification functions resulting from the MCS for the ground response analysis at BH23 (sample size is equal to 1000)

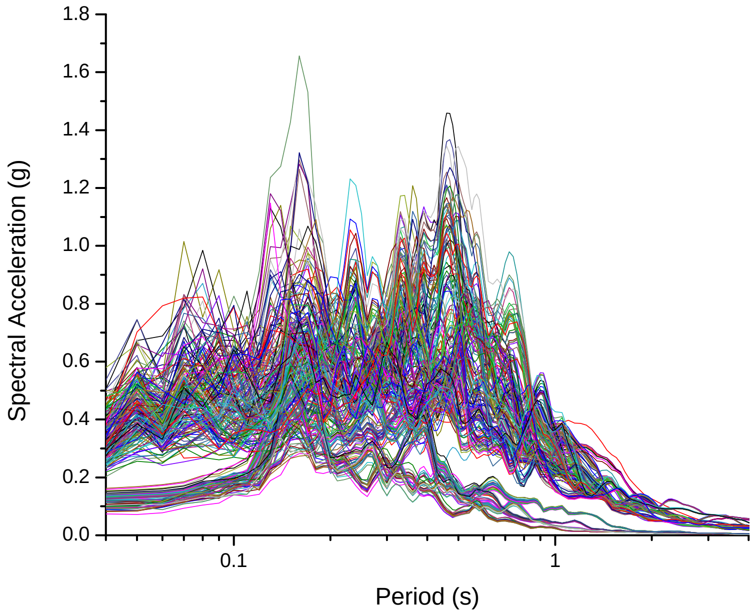

Figure 5. Response spectra at the ground surface resulting from the MCS for the ground response analysis at BH23 (sample size is equal to 1000)

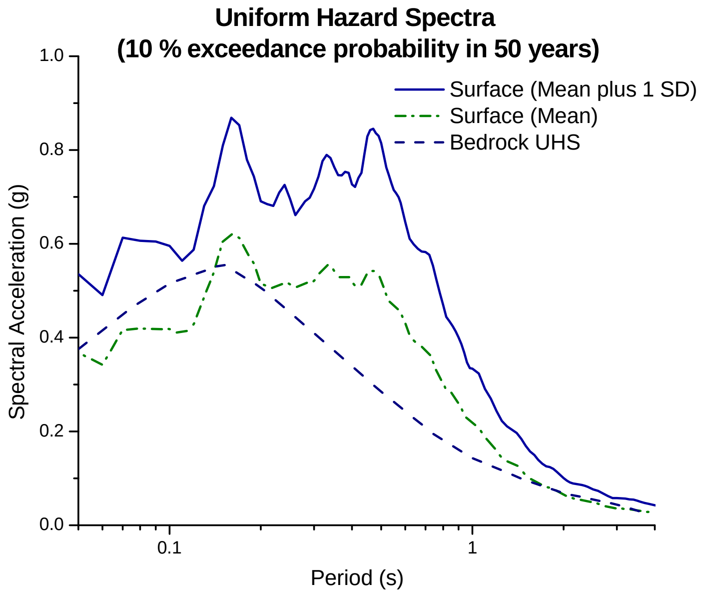

Figure 6. Uniform hazard spectra with 10% exceedance probability in 50 years at the ground surface and its comparison with the UHS target spectrum at the bedrock level for BH23

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