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ABSTRACT

This paper deals with the stochastic seismic analysis of a site in the city of Algiers (Algeria), which is composed by superposed layers over an elastic halfspace. Layers heights are assumed to be random variables with a lognormal distribution, which is suitable for strictly non-negative random variables.

The analysis is carried out via Monte Carlo simulations coupled to the stiffness matrix method. A parametric study is conducted do derive the stochastic behavior of the extreme ground acceleration, its response spectrum and the transfer function. The soil height coefficient of variation is varied from 0 (corresponding to the homogeneous case) to 0.5. The input seismic acceleration corresponds to Boumerdes earthquake (Algeria, May 21st, M_w=6.5).

Layers height variability causes an increase of the NS component of the peak ground acceleration and a decrease of the EW component. The soil profile height heterogeneity affects the form of the PGA but slightly its amplitude.

This variability induces a slight increase of the soil profile fundamental frequency and an extension of the frequency content, indicating that the resonance phenomenon concerns a larger number of structures. The soils height randomness acts as the variation of the incident angle: decreasing the amplitude and shifting of the resonant frequencies.

The maximum values of the confidence interval of the transfer function, for both mean and standard deviation, correspond to eigen-frequencies, which implies that the uncertainty is amplified by the resonance phenomenon

INTRODUCTION

Site effect has a significant influence on the earthquake ground motion. It depends on the material properties, surface topography and incoming seismic motion. The most important site effects are the amplification due to the impedance contrast and the frequency content filtering. These phenomena cause change of the seismic motions characteristics and damage concentration. Seismic risk assessment requires then analysis at a local scale. The local site features, such as the variation of thickness, soil layers properties and bedrock depth, have important effects on the surface ground motions. The Boumerdes earthquake (Algeria, May 21st 2003) has demonstrated the importance of the site effect, since in a same region the effects where significantly different from an area to another. The city of Algiers, located at 50 km distance from Boumerdes, was greatly influenced by this earthquake in spite of the distance. Due to the complexity of Algiers site, the use of deterministic methods appears as very restrictive as they might not take into account the whole phenomena inherent with the site effects. It is then required to make detailed studies for each area of the site in order to analyze the seismic movement amplification due to site effect (Manolis, 2002; Zerva, 2002).

For this purpose, a probabilistic study should be carried out: the soil depth is considered as a random variable. The heterogeneity effect of the bedrock depth is considered. However, the data concerning this parameter are not available for the whole profile since in-situ tests are restricted to a certain depth and no information is available below this level. To lead a probabilistic study, a significant number of samples are necessary. Such samples are incidentally rarely available. In-situ tests conducted to determine the soil profile characteristics were limited to a certain depth and no information is available about the layers heights and the mechanical characteristics below it. Recent works have shown that depth to bedrock influences significantly the amplification across a wide frequency range (Kawase and Aki, 1989). Olsen et al. (1995) indicate that the highest ground motion amplification occurred near the edges of the deepest portions of the basin and Takahashi et al. (2006) have shown that earthquake damage was more serious where the sensitive clay layers were thicker.

SEISMIC ANALYSIS OF A HETEROGENEOUS SOIL PROFILE

The use of numerical methods such as finite element method (FEM) or boundary element method (BEM) in the seismic response of multilayered soils introduces a significant number of variables and the dimension of the problem becomes very large. The stiffness matrix method is a convenient tool to avoid this disadvantage (Kausel and Roësset, 1981; Kausel, 2006). It consists of solving the problem in the frequency - wavenumber domain, and the solution in the space domain is obtained by analytical inverse spatial Fourier transform (Kausel and Roësset, 1981; Prosper, 2001; Kausel, 2006; Chen, 2005). The elastic wave equation of a homogeneous medium in the (x,z) plane, subjected to P, SV and SH waves, in the frequency - wavenumber domain is

$$k^2 D_{xx} u + k\, B_{xz} \frac{\partial u}{\partial z} - D_{zz} \frac{\partial^2 u}{\partial z^2} - \rho \omega^2 u = 0 \tag{1}$$

where ρ is the mass density, k is the wavenumber, ω is the pulsation, u is the displacement vector and the matrices D_{xx}, D_{zz} and B_{xz} are given by the expressions

$$D_{xx} = \begin{bmatrix} \lambda + 2\mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \mu \end{bmatrix} \tag{2}$$

$$D_{zz} = \begin{bmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \lambda + 2\mu \end{bmatrix} \tag{3}$$

$$B_{xz} = \begin{bmatrix} 0 & 0 & -(\lambda + \mu) \\ 0 & 0 & 0 \\ \lambda + \mu & 0 & 0 \end{bmatrix} \tag{4}$$

λ is the Lamé constant and μ is the shear modulus. The displacement can be given by

$$u = \begin{bmatrix} e^{-kpz} & 0 & -s\,e^{-ksz} & e^{kpz} & 0 & s\,e^{-ksz} \\ 0 & e^{-ksz} & 0 & 0 & e^{ksz} & 0 \\ -p\,e^{-kpz} & 0 & e^{-kpz} & p\,e^{kpz} & 0 & e^{ksz} \end{bmatrix} \{C\} \tag{5}$$

Here $\{C\}$ is a vector of six constants of integration, i is the complex number and the coefficients p and s are expressed as

$$p = \sqrt{1 - \left(\frac{\omega}{k\,C_p} \right)^2} \qquad s = \sqrt{1 - \left(\frac{\omega}{k\,C_s} \right)^2} \tag{6}$$

C_p and C_s being P-wave and S-wave velocities respectively.

For a stratified soil consisting on N layers ($N+1$ interfaces) over an elastic halfspace, subjected to P or SV waves generated in the halfspace, by recourse to substructuring techniques (Kausel, 2006), one obtains an equation of the form

$$[K]\{U\} = \{F\} \tag{7}$$

where K is the stiffness matrix, $\{U\}$ is the displacement vector and $\{F\}$ the force vector.

In geotechnical engineering, an important difference between the observed and the predicted behavior of soils is noted which is the consequence of the variability in soil properties. Soils are heterogeneous; their heterogeneity reflects varying geological soil formation processes. This variability depends on the earthquake input (seismic waves) and the site characteristics, and is rather difficult to describe. In this study layer height is assumed to be a random variable with a lognormal distribution. The mean and variance for soil height are obtained by the following expressions

$$\sigma^2_{\ln H} = \ln\left(1 + \frac{\sigma^2_H}{\mu^2_H} \right) \tag{8}$$

$$\mu_{\ln H} = \ln(\mu_H) - \frac{1}{2}\sigma^2_{\ln H} \tag{9}$$

where $\mu_{\ln H}$ and $\sigma^2_{\ln H}$ are respectively the mean and variance for lognormal distribution and μ_H and σ^2_H stand for soil profile height mean and variance respectively.

NUMERICAL RESULTS AND DISCUSSIONS

The present analysis concerns the investigating of the seismic behavior of a heterogeneous soil profile site, accounting for the variability of the layers height. The seismic parameters considered in the present study are the maximum ground acceleration and its corresponding response spectrum and the transfer function. This analysis is carried out at the Dar-el-Beida site in Algiers (Algeria). The soil profile characteristics of the considered site are presented in Table 1 (Harichane et al., 2005).

Layers heights are assumed to be random variables with a lognormal distribution. Mean values of layers heights (μ_H) are given in Table 1 and their coefficients of variation (Cv_H) vary from 0 (corresponding to the homogeneous case) to 50% (Badaoui et al., 2004; Badaoui et al., 2006; Badaoui et al., 2008; Badaoui et al., 2009).

Table 1. Mean soil profile Characteristics of the Dar-el-Beida site (Algiers, Algeria)

Layer no	Thickness (m)	Damping ratio (%)	ρ (kg/m3)	C_s (m/s)	C_p (m/s)
1	1.6	4.9	1211	184	429
2	4.8	3.7	1182	291	593
3	3.2	2.4	1273	319	614
4	7.1	3.4	1350	395	729
Halfspace	-	0.0	1500	450	779

for each parameters set (μ_H , Cv_H),N_{sim}=1000 simulations are performed and N_{sim} values of the seismic response parameters are obtained. Therefore, the statistics, i.e. the mean and variance as well as the 95% confidence interval for the results are calculated in order to investigate the probabilistic effect of soil height on the seismic response. The output parameters statistics μ_{RS} and σ^2_{RS} are obtained by using the following formulas

$$\mu_{RS} = \exp\left(\mu_{\ln RS} + \frac{1}{2}\sigma^2_{\ln RS}\right) \tag{10}$$

$$\sigma^2_{RS} = \exp\left(2\,\mu_{\ln RS} + \sigma^2_{\ln RS}\right)\left(e^{\sigma^2_{\ln RS}} - 1\right) \tag{11}$$

where μ_{RS} and σ^2_{RS} are the output parameters statistics and $\mu_{\ln RS}$ and $\sigma^2_{\ln RS}$ are the corresponding lognormal distribution statistics.

From the E-W and N-S input accelerations in time and frequency domains, one may conclude that the E-W component is larger than N-S, and central frequencies (peak frequencies) are 4.1 Hz for the E-W component and 9.3 Hz for the N-S component, while predominant frequencies (mean frequencies) are 4.9 Hz for E-W and 6.0 Hz for N-S. From the response spectra for both E-W and N-S input accelerations, it appears that the horizontal response spectrum shows a high frequency content starting at 3 Hz (i.e. T≈0.330 sec) with a central frequency around 8 Hz (i.e. T≈0.125 sec).

Maximum ground acceleration

From the statistics (mean and standard deviation) and the 95% confidence interval of the maximum ground surface acceleration for the EW direction, with respect to the layers heights coefficient of variation C_{vH}, it is shown that this variability causes a slight decrease of the response with a constant stage for small C_{vH} values, see Figure 1.

Mean value of the PGA varies from 0.84g and 0.82g (2%). This means that the heterogeneity of the layers heights affects the form of the PGA variation but slightly its amplitude. Standard deviations of all PGA components increase in a similar way, and have almost a linear variation with the heterogeneity of the soil height.

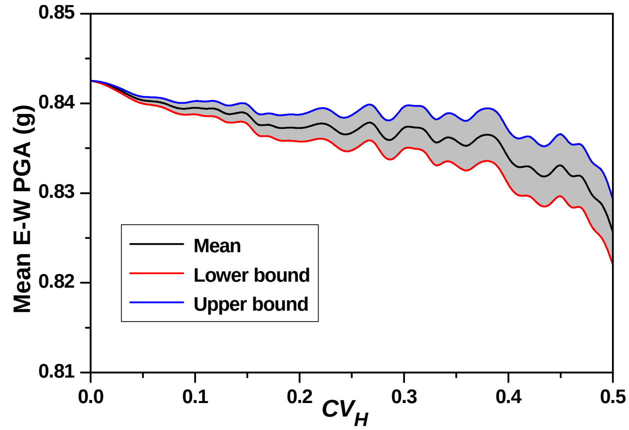

Fig. 1. E-W peak ground acceleration statistics.

Response spectra

The statistics of the pseudo response spectra for maximum ground surface accelerations, for C_{vH} = 0.0, 0.2 and 0.5, show that as soil height heterogeneity increases, there is a decrease of the mean values for predominant periods and an increase elsewhere with a slight shift of the fundamental period, as illustrated by Figure 2.

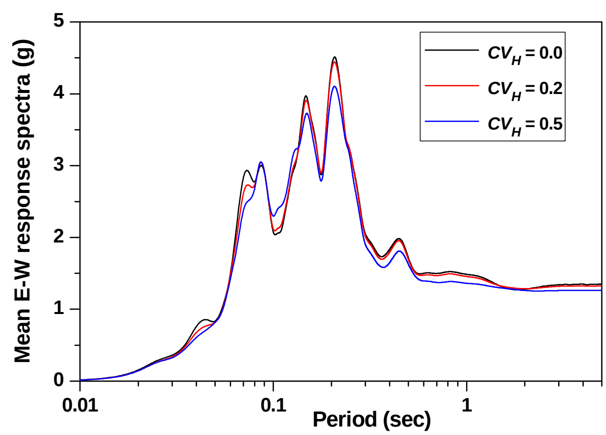

Fig. 2. E-W response spectra statistics.

There is a great effect on standard deviations at the resonance period because the high values of the response spectra at this period induce an important dispersion.

Transfer function

The transfer function (amplification ratio) is calculated for horizontal direction (Figure 3). The soil height heterogeneity causes an important decrease of the eigen-frequencies amplitudes. For the fundamental frequency, the amplitude of the transfer function decreases from 1.61 to 1.52 (6%) when

C_{vH} varies from 0.0 to 0.5. A weak increase of the eigen-frequencies is observed.

The standard deviation of the transfer function is important for the eigen-frequencies of the soil profile. Furthermore, according to the 95% confidence interval of the transfer function corresponding to C_{vH} = 0.5, one may conclude that for both mean and standard deviation, maximum values of this interval correspond to eigen-frequencies, which implies that the uncertainty effect is amplified by the resonance phenomenon, see Figure 8.

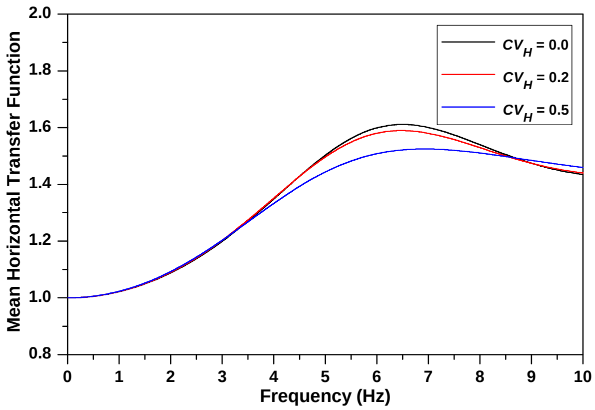

Fig. 3. Horizontal transfer function statistics.

As the layers height heterogeneity increases the frequency content increases too, indicating that the soil becomes more rigid and that a larger field of frequencies (i.e. a more significant number of structures) is concerned by the resonance phenomenon. The soils height randomness acts as the variation of the incident angle, i.e. a decrease of the amplitude and a shift of the resonant frequencies (Wang and Hao, 2002).

CONCLUSION

This paper deals with the investigation of the seismic response behavior of a heterogeneous layered soil profile site accounting for the randomness of the layers thickness. The seismic parameters considered in present study are: the maximum ground acceleration and its corresponding response spectrum, the transfer function and the short and mid-period amplification factors.

Layers height variability causes a slight decrease of the EW component of the PGA. This heterogeneity affects the form of the PGA but slightly its amplitude.

The heterogeneity of the soil height supports a decrease in the amplitude of the pseudo response spectra with a slight increase of the resonance period. A decrease of the amplification function at the eigen-frequencies is observed with a weak increase of these frequencies as well as the frequency content, indicating that a more significant number of structures is concerned by the resonance phenomenon and that the uncertainty effect is amplified by the resonance phenomenon.

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