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EFFECT OF 1D VERTICAL VARIABILITY OF SHEAR MODULUS ON THE SEISMIC RESPONSE OF SITES

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Abstract

Urban development is increased and the construction of building on poor quality soils becomes non avoidable which increases the geotechnical risk. Below these circumstances, the probabilistic approaches to study the behavior of a soil profile in a given environment have been proposed in recent years. The purpose of this research work is to study the effect of vertical variability of soil shear modulus on soil seismic response using the probabilistic approach. Two types of heterogeneity are considered: (1) heterogeneity due to the random distribution of the shear modulus in a soil profile; (2) heterogeneity of soil layer with shear modulus increasing linearly with depth. The first heterogeneous soil models are generated by Monte Carlo simulation. The spatial variation of the shear modulus is controlled by the variation coefficient parameters. The second heterogeneous soil models are assumed to have shear modulus increasing linearly with depth. These heterogeneous soils are generated and then integrated into the computer program based on the one dimensional wave propagation, resulting in seismic responses at the 'free field' soil. To demonstrate and show the importance of considering heterogeneities in the model, the results are compared with examples of deterministic analysis by means of the experimental value of shear modulus obtained from a specific site in Algeria.

Keywords: *Shear Modulus, Heterogeneity, Random Distribution, Increasing Linearly, Soil Seismic Response.*

1   INTRODUCTION

In geotechnical practice, the determination of soil properties is based on tests carried out on a limited number of samples in the laboratory or on site. Soil state variables in space and time are due to complex geological conditions. Their properties change from a point to another. Due to the uncertainty associated with their inherent spatial variability, and limited available information, soil properties can be considered as random variables. Moreover, poor soil sampling procedures, test procedures, characteristics of the test setup device and operator experience can have a large impact on the measured geotechnical properties. The probabilistic approach is often used in engineering sciences to represent and decrease these uncertainties. It attempts to take into account all the uncertainties affecting the properties of soils, and allow the engineer to make the decision that bringing more objectivity; it assumes that the characteristics are variables defined by a mean, a standard deviation and a distribution law. To consider these uncertainties using the probabilistic approach, soil properties are treated as random variables. These random variables are functions defined on a sample space to represent quantities that can change. In practice, a random variable is where the estimated value is uncertain, but a certain probability can be assigned to any specific value (take values from a finite or countable set) "for discrete random variables" or within any value from an interval on a real line "continuous random variables".

Several studies have been conducted taking into account uncertainty in geotechnical engineering, Tian and Jie [1] conducted a study of the uncertainty of soil parameters, regarding the shear wave velocity (VS), thickness (h), density and damping for the propagating of one-dimensional wave. Specific conclusions were drawn. Nour [2] studied, two-dimensional seismic response, using Monte Carlo simulations combined with the deterministic method of shear modulus, critical damping and Poisson's ratio of soil properties. The results showed a significant attenuation of the tendency of the acceleration at the ground surface compared to the homogeneous case. Dominic et al [3] carried out a study of the importance of the spatial variability of soil properties on the surface response spectrum using Monte Carlo simulation based on the Popescu methodology [4]. They concluded that local conditions are important according to the gradient of the stiffness of the profile and intensity of the movement and that further studies should be performed. Paolo and Cornell [5] presented a probabilistic work to study the effect of soil layers on the estimation of the nonlinear amplification function, AF (f) and the acceleration response spectrum for a frequency range of the oscillator of the structures. The results revealed that AF (f) depends strongly on the intensity of the input soil movement at the same oscillator frequency, for the two soil types studied (sand and clay). Andrade and Borja [6] performed a combined stochastic-deterministic analysis of the local site response. To compare the sensitivities of equivalent linear and non-linear analysis procedures, two computer codes SHAKE and SPECTRA were used. The soil variability as well as the frequency and duration of earthquakes were considered in this study. The results showed that SPECTRA has approximately the same sensitivity as SHAKE.

Other recent typical examples include the work of Li and Assimaki [7], Johari A. [8] and Menzer Pehlivan et al [9] examined the special variability of soil on the prediction of a strong soil motion, where the consequences of spatial variability on the seismic response are not well understood. The basic characteristics of any layer are the shear wave velocity, the thickness and the non-linear properties of soil. The values of these properties in nature through a site vary from one point to another and there is always uncertainty in their measurement, this is a major contributor to uncertainty in geotechnical engineering analyzes.

2 PROBABILISTIC METHOD OF INDIRECT SIMULATION OF NON-GAUSSIAN RANDOM FIELDS

The probabilistic method of indirect simulation of non-Gaussian random fields is based on the theory of random fields. This approach is based on the decomposition of random variables as described by Fenton [10].

The algorithm that allows the generation of $\Delta f_p(z)$ is described as follows:

$$\Delta f_p(z) = \sum_{n=1}^{N_P} \Delta g_{pn}(z)$$

(1)

With Np is the number of soil properties to be simulated. The Gaussian random field with Np variables, one-dimensional, with zero mean and unity variance $\Delta g_{pn}(z)$ can be simulated as follows [11, 16]:

$$\Delta g_{pn}(z) = \sqrt{2} \sum_{l=0}^{N} A_{l,pn} \cos(k_l z + \Omega_{l,pn})$$

(2)

With
For multivariate fields

$$A_{l,pn} = H_{pn}(k_l)\sqrt{2\Delta k}$$

(3)

For uni-variate fields

$$A_l = \sqrt{2S(k_l)\Delta k}$$

(4)

Equation (3) also can ensures the inter-property correlation, $\Omega_{l,pn}$ are random phases uniformly distributed in the interval $[0\ 2\pi]$. The coefficients Hpn are obtained from the inter spectral density matrix in the wave number domain $S(\mathcal{K})$, the latter is a real, symmetrical matrix, and positive definite. The elements of the matrix H are obtained from the Cholesky decomposition of the symmetric matrix S which is defined by:

$$S(k) = \begin{bmatrix} S_{11}(k) & S_{12}(k) & \cdots & S_{1Np}(k) \\ S_{21}(k) & S_{22}(k) & \cdots & S_{2Np}(k) \\ \cdots & \cdots & S_{pipi}(k) & \cdots \\ S_{Np1}(k) & S_{Np2}(k) & \cdots & S_{NpNp}(k) \end{bmatrix}$$

(5)

The matrix Hpn is assumed to be lower triangular:

$$H(k) = \begin{bmatrix} H_{11}(k) & 0 & \cdots & 0 \\ H_{21}(k) & H_{22}(k) & \cdots & 0 \\ \cdots & \cdots & \cdots & 0 \\ H_{Np1}(k) & H_{Np2}(k) & \cdots & H_{NpNp}(k) \end{bmatrix}$$

(6)

with $\mathcal{K}$ is the number of waves which satisfies:

$$\begin{cases} k_l = l.\Delta k \\ k_u = N.\Delta k \end{cases}$$

(7)

The wavenumber step $\Delta \mathcal{K}$ is evaluated from the representation of $S\,\mathcal{K}$ and by evaluating the cut-off wavenumbers values $\mathcal{K}u$ for N increments, $\mathcal{K}u$ is defined by:

$$k_u = \frac{1}{a}\sqrt{\ln\left(\frac{1}{\lambda^4}\right)} \quad ; \lambda = 0.001 \tag{8}$$

a is a parameter statistic, which is obtained from a non-linear regression of experimental data.

In this study, we consider one-dimensional, univariate, homogeneous but non-Gaussian field with mean zero and spectral density function given by [2]:

$$S(k) = \frac{\sigma^2\big|_{\sigma=1}\,a}{2\sqrt{\pi}}\exp\left[-\left(\frac{ka}{2}\right)^2\right] \tag{9}$$

In order to considerably reduce the computing time, the digital generation of sample functions of equation (2) is easily calculated using the Fast Fourier Transform (FFT), developed by Yamazaki and Shinozuka [17] and modified by Zerva [18].

The analysis carried out in this paper considers λ (is a small real number close to zero) equal to 0.001.

3 SPATIAL VARIABILITY OF UNBOUNDED SOIL PROPERTIES

Soil properties such as elastic modulus E, shear modulus G, permeability k, etc., are assumed to be lognormally distributed. This choice is motivated by the fact that these properties are positive parameters, and that the lognormal distribution makes it possible to analyze their great variability. The expression of the shear modulus for example is given by [2,10]:

$$\lambda_G(z) = \exp\left[\lambda_{0G}(z) + \xi_G \Delta f_G(z)\right] \tag{10}$$

With:

$$\begin{cases} \xi_G^2 = Ln\left(1 + \dfrac{\sigma_G^2}{\lambda_{0,G}^2}\right) \\[2mm] \lambda_{0G}(z) = \ln(\lambda_{0,G}) - \dfrac{1}{2}\xi_G^2 \end{cases} \tag{11}$$

Where $\lambda_{0,G}$ and σ_G^2 are respectively stand for shear modulus means and variance.

CV_G: Coefficient of variation: To provide a dimensionless expression of the uncertainty inherent in a random variable.

4 HETEROGENEITY OF SOIL LAYER WITH SHEAR MODULUS INCREASING LINEARLY WITH DEPTH

In this proposed approach the soil profile is assumed to have shear modulus increasing linearly with depth. In the upper layer, of thickness h_1, the shear modulus is supposed to vary according to [19]:

$$G_1(z) = G_0(z/h_1)^p \tag{12}$$

Where z is the depth counted positively downwards from ground surface, G_0 is the shear modulus at depth h_1, p is an arbitrary exponent, which takes values in range $0 \leq p < 2$. The

parameter p can be determined by a least square fit through the measured values of the shear wave velocity $\hat{V}(z)$ and is given by Ref. [20]:

$$p = \ln V_{s1} \frac{1}{h1} \int_0^{h_1} \ln\left(\frac{z}{h_1}\right) \ln \hat{V}(z) dz \qquad (13)$$

Where V_{s1} is the shear wave velocity at depth h_1

For the underlying layer the shear modulus is assumed to be:

$$G_2(z) = G_0 + G1\left(z/h_2\right) \qquad (14)$$

Where z is counted from the layers interface and h_2 is the thickness of second layer and G_0+G_1 is the shear modulus at depth h_2.

5   RESULTS OF THE DYNAMIC RESPONSE OF A HETEROGENOUS ONE-DIMENSIONAL SOIL PROFILE

▪ **Site variability Effects (shear modulus): the case of Souidania**

This example deals with the vulnerability of a site with an inclined topography, with a slope that varies from 4% to 5%, (figure 10). The site is located at Souidania, located in the southwestern suburbs of Algiers and occupies an area of around 6 ha [21].

Fig. 1. Location of the project (Google Earth, October 2016)

It is shown in figures 2 and 3 ten realizations of the shear modulus for different values of CVG. The effect of site variability is therefore an essential parameter in an urban environment which must be evaluated to better define the lateral variability of the seismic movement of the soil, with immediate consequences on the response of structures and their damage.
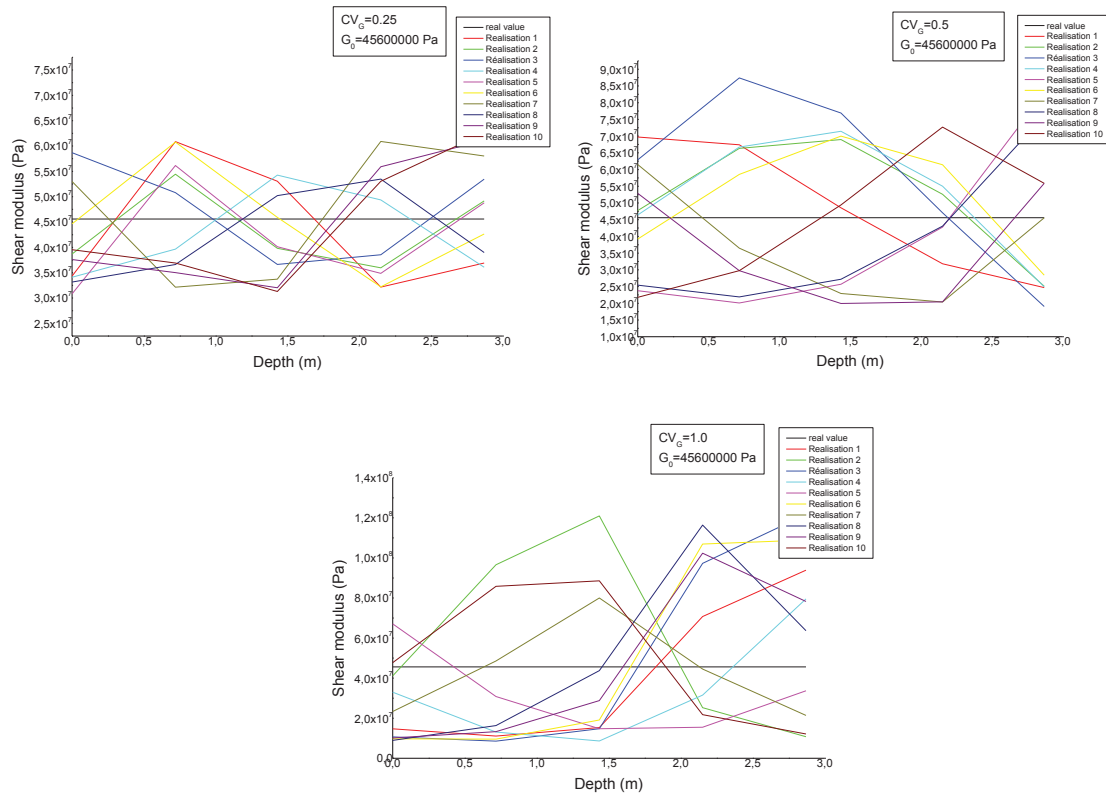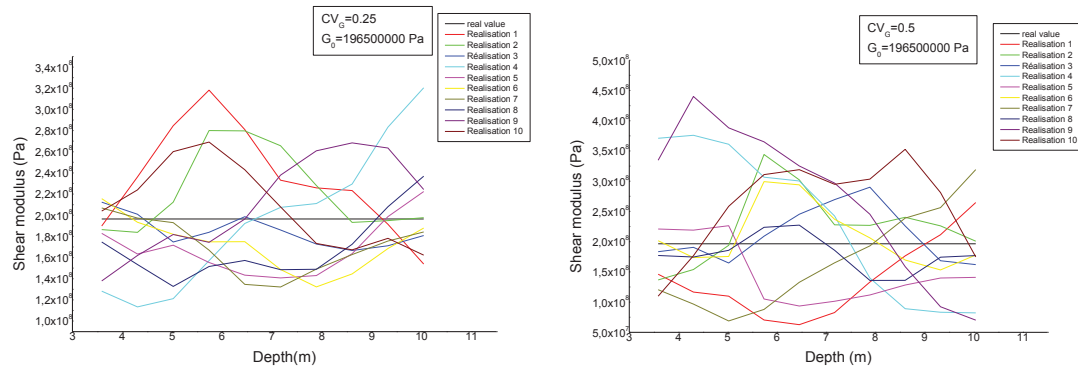
- **First layer**

Fig. 2. Ten realizations of variations in shear modulus, first site layer, for different values of CV_G.
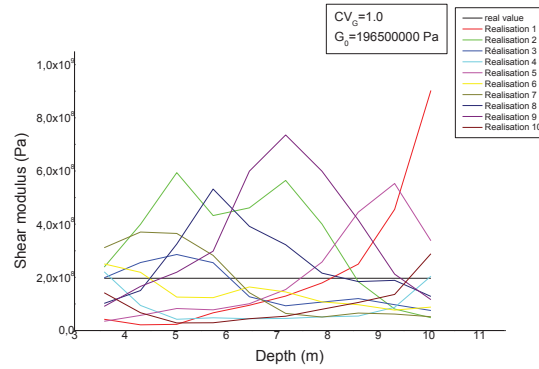
- **Second layer**

Fig. 3. Ten realizations of shear modulus variations, second site layer, for different values of CV_G.
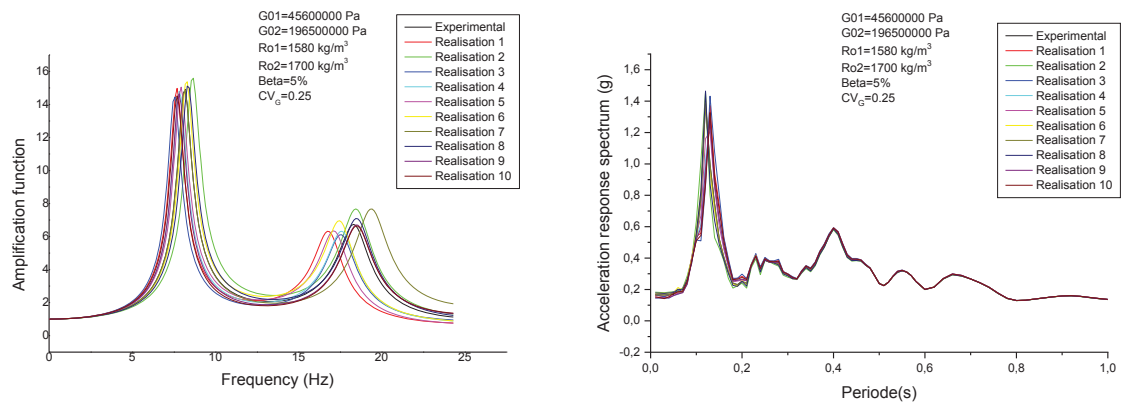

Fig. 4. Seismic amplification and the response spectrum in acceleration at the surface of the experimental case and of ten realizations according to the variability of the shear modulus G for a value of $CV_G = 0.25$.
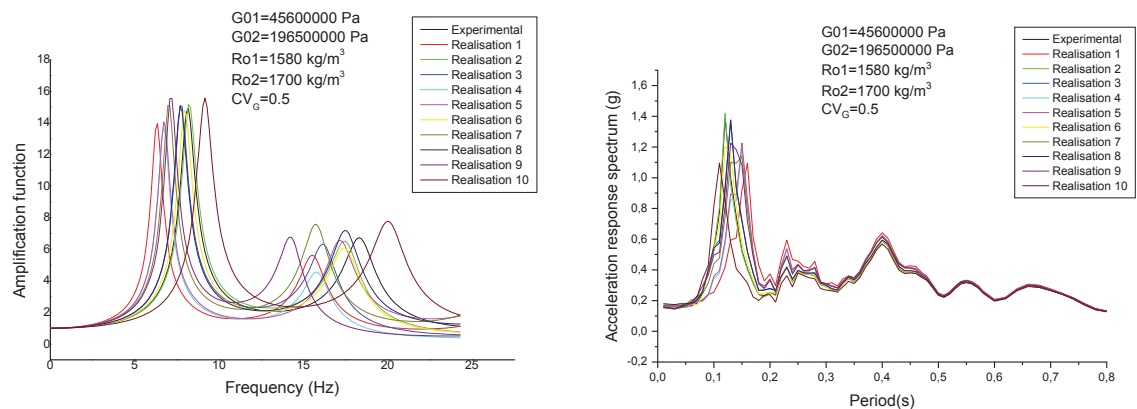

Fig. 5. Seismic amplification and the response spectrum in surface acceleration of the experimental case and ten realizations according to the variability of the shear modulus G for a value of $CV_G = 0.5$.
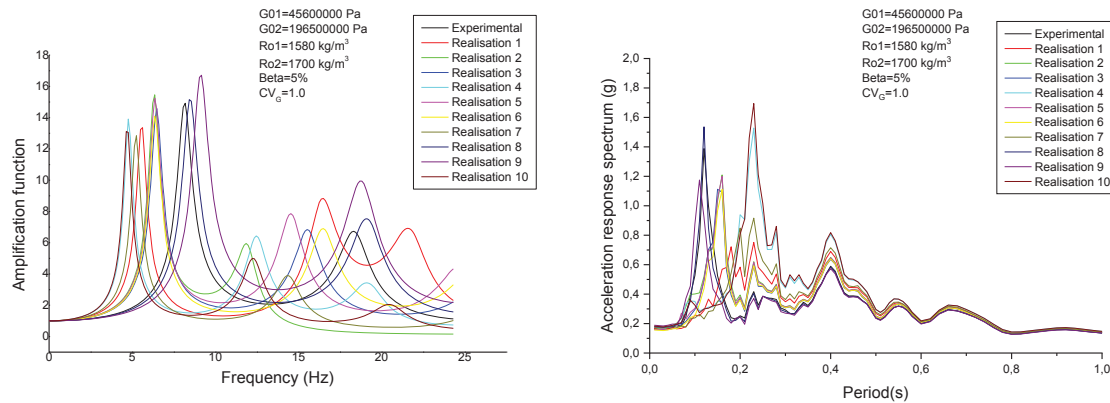
Fig. 6. Seismic amplification and the response spectrum in acceleration at the surface of the experimental case and of ten realizations according to the variability of the shear modulus G for a value of $CV_G = 1$

From figures 4, 5 and 6, it is clearly seen that the variation of the shear modulus has great importance on the seismic amplification of the soil and this amplification varies according to the coefficient of variation CV_G where the value of the CV_G varies from 0.25 slightly heterogeneous to the value 1.00 strongly heterogeneous. Figure 7 shows a comparison between the case of heterogeneous experimental case, the cases of average of the ten realizations for each CV value and the case of shear modulus increasing linearly with depth.
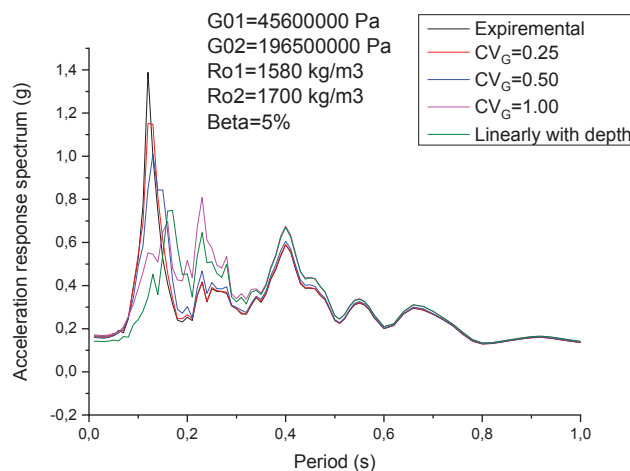

Fig.7. Surface acceleration response spectrum difference between the experimental case, the case of Monte Carlo as a function of the variability of the shear modulus G for different CV_G values and the case of shear modulus increasing linearly with depth.

From the curves we can clearly see the differences between the studied cases, and that the probabilistic seismic response of heterogeneous soil profile via Monte Carlo simulations, for the value of CV = 0.25, is more equivalent to that of the seismic response of experimental case. On the other hand, we have observed an attenuation compared to the other cases of the value of CV = 0.5 and CV =1. Furthermore, For the case of the shear modulus increasing linearly with depth, the value of the response spectrum is identical to the probabilistic seismic response of heterogeneous soil profile via Monte Carlo simulations for the case of CV = 1.

6   DISCUSSION AND CONCLUSIONS

In this paper the acceleration response spectrum of the heterogeneous seismic amplification soils is analyzed. The random soil properties considered is the shear modulus, modeled by random spatial fields. The random field for the shear modulus is obtained by adopting the lognormal distribution, which allows its great variability to be analyzed.

As a summary of this article, we can recapitulate the following comments

- The increase in the coefficient of variation of the shear modulus induces a decrease in soil amplification and the peak acceleration response spectrum for the one-dimensional case. On the other hand, it is observed that increasing the coefficient of variation of the shear modulus also causes a filtering effect which slides the fundamental frequency of the system towards low frequencies, and causes attenuation of high frequencies. In this case, the simulated soil becomes softer compared to the homogeneous soil ($CVG = 0$).
- For the case of shear modulus increasing linearly with depth, the value of the response spectrum is identical to the probabilistic seismic response of heterogeneous soil profile via Monte Carlo simulations for case of CV = 1.

The results obtained indicate that the seismic response is related to the shear modulus variability. In addition, it is observed that the increase in the coefficient of variation of the shear modulus induces a decrease in the peak value of the response spectrum in acceleration for the one-dimensional case. The method described in this paper, by analyzing several realizations, can reduce the geotechnical risk.

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