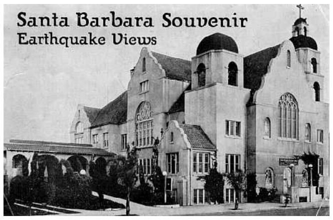

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USE OF GEOSTATISTICS AND RANDOM FIELD THEORY TO ACCOUNT FOR UNCERTAINTY AND SPATIAL VARIABILITY OF SOIL PROPERTIES IN TWO-DIMENSIONAL SITE RESPONSE ANALYSES

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ABSTRACT

Seismic amplification characteristics of ground motion are influenced by the geotechnical properties of soil deposits and the associated uncertainties. Geotechnical systems are often represented with deterministic models, both for the soil parameters and for their spatial distribution. However, a deterministic ground response analysis does not allow to assess the uncertainty associated to the assumed soil parameters. To overcome this problem a number of methods are available. The spatial variability of the soil parameters can be taken into account by coupling Monte Carlo Simulations (MCS) with Geostatistics (GS) and Random Field Theory (RFT). This work is aimed to illustrate and compare the results of 2D fully stochastic site response analyses using MCS associated with GS and RFT. Several sets of one hundred realizations of model parameters were generated using MCS coupled with GS and RFT methods to reproduce the spatial variability of soil parameters. Variability of seismic input was also taken into account by considering a set of spectrum-compatible natural records. An advanced numerical program for the seismic analysis of continua was used for setting the geotechnical model and performing ground response analyses. The response in terms of specific ground motion parameters was computed, highlighting and comparing advantages and limitations of GS and RFT methods.

INTRODUCTION

The influence of local site conditions on the nature of earthquake damage has been recognized for many years. In current engineering practice, site response analysis is generally performed using an idealized one-dimensional soil profile, which is characterized with best estimate values for the geotechnical properties. However, soil mechanical properties, which define how seismic energy manifest itself on the surface, are subjected to a sizable variability, for example, coefficients of variation (CoV) of 40% and 50% are not uncommon for some soil parameters [Phoon, 2008]. As a result, the execution of deterministic analyses of seismic amplification does not necessarily represent the response at a site in which the uncertainties of the parameters used to develop the subsoil model are large. Another important aspect to consider is the variability of seismic input: CoV for "rock" sites can reach up to 50% of the mean value of Peak Ground Acceleration (PGA) for a given magnitude and rupture distance [Abrahamson and Silva, 1997]. If the variability due to magnitude and distance is also considered, CoV values can reach values as large as 150% [Arroyo and Sanchez Silva, 2005]. Hence, in order to perform a reliable analysis, two major issues should be considered: variability of soil properties and variability of seismic input. This study illustrates the implementation of two different methodologies to estimate site effects, taking into account the variability of soil properties as well as the variability of the seismic input. The two approaches are respectively based on Geostatistics (GS) with Kriging interpolation, and on a Random Field (RF) description of the model parameters. In both cases Monte Carlo Simulation (MCS) is used. The seismic response analyses are then performed with FLAC 2D [Itasca, 2000], an advanced finite differences numerical program for numerical simulations of geotechnical systems.

CASE STUDY

The proposed methodologies were applied on a two-dimensional soil profile. The geotechnical characterization was based on a site in Vicoforte, a municipality of Cuneo in the southwest of the Piedmont region in northern Italy. This is the location of the Vicoforte "Regina Montis Regalis" Basilica, which has the largest elliptical dome in the world. Throughout the years three major geotechnical investigation campaigns were carried out at the site. These provided a large amount of data needed in order to implement GS and RF.

Seismic Input:

A Probabilistic Seismic Hazard Analysis (PSHA) was performed to define the seismic input at the site. The outcome of the PSHA are the horizontal and vertical hazard curves in terms of PGA, and the Uniform Hazard Spectra (UHS) of accelerations. Reference return periods of 72, 475, 975 and 2475 years on rock outcropping (or stiff site) were considered. Deaggregation was performed in order to identify the "controlling earthquakes" at the site. Finally, different suites of spectrum-compatible and seismo-compatible natural acceleration records on rock were selected for the different return periods, in order to perform site response analysis.

For this paper, only the selected set of input motions corresponding to the 475 years return period was used. The value of PGA for the selected return period is 0.1g. Figure 1 a) shows the computed UHS corresponding to the 475 years return period while Fig.1 b) shows the selected set of natural spectrum-compatible records together with the mean spectrum of the set. Further information regarding other return periods and the outcome of the hazard study can be found in Lai *et al.* [2009].

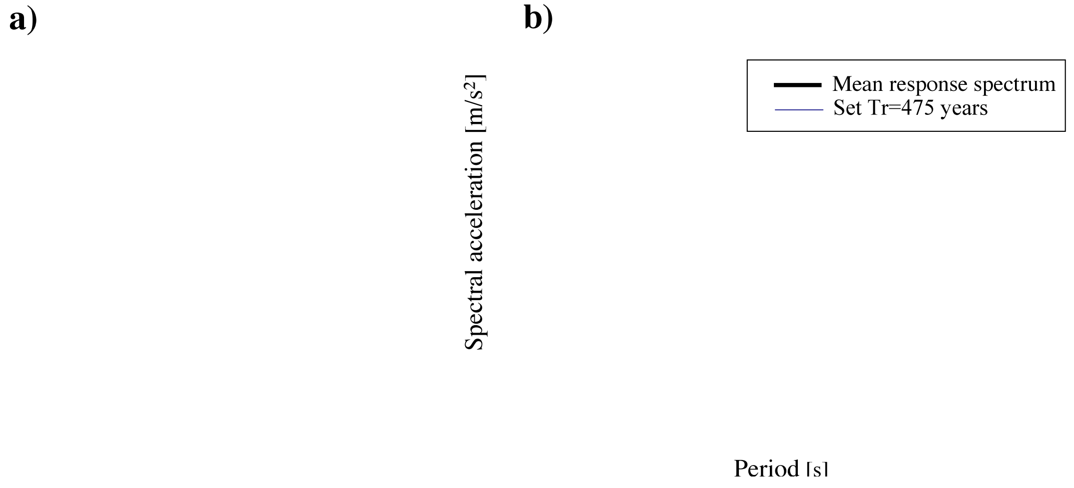

Fig. 1 a)Horizontal component of the Uniform Hazard Spectrum (UHS) for the 475 years return period used in this study; b)Elastic response spectra of the 7 real accelerograms selected for the 475 year return period along with the mean spectrum of the set.

Geotechnical Characterization

The data used in this study were obtained from previous geotechnical investigation campaigns. The first one was performed in 1976 and consisted of borehole drilling, Standard Penetration Tests (SPT), and laboratory testing of undisturbed soil samples. In 2004 a second campaign was carried out. Tests performed included soil sampling, laboratory testing and cross-hole test (CHT). Finally, in 2008 geophysical characterization of the site was performed using state-of-the-art techniques. The tests performed included Multi-station Analysis of Surface Waves (MASW), Refraction Microtremors (ReMi), Nakamura survey, 3D electric tomography, and 2D seismic tomography. The 2D section used in this study was chosen to comply with the results of the investigation campaign, and is oriented in the North-South direction, which is parallel to the longitudinal axis of the Basilica. The definition of the stratigraphic model used to perform the site response analysis has been done combining the results obtained from the boreholes and cross-hole test (CHT) positioned very closely to the section under study. Figure 2 shows the position of the CHTs (CHT1, CHT2) and the location of 3 boreholes (S1, S2, S3) that were drilled along the selected section. Also shown in Fig. 2 is the 2D seismic tomography, representing the shear wave velocity (Vs) obtained along the section. This information will be later use as input in the GS methodology.

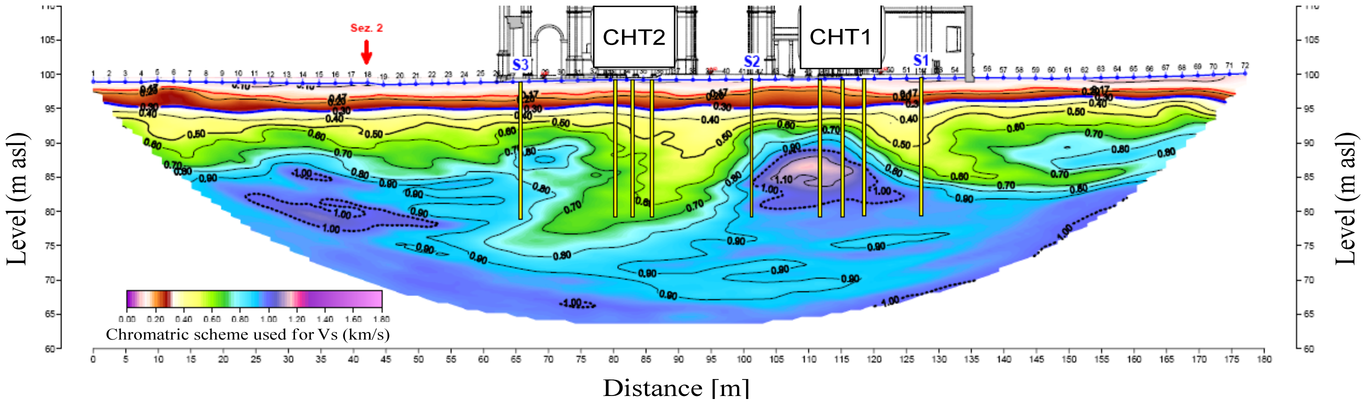

Fig. 2 Two-dimensional seismic tomography of Vs obtained at the site. Also plotted in the figure are the positions of CHTs and of the boreholes carried out in previous geotechnical characterization campaigns.

Three different material formations were identified at the site. The surface layer consists of clayey-silt material with variable thickness ranging from 4 m to 6 m. A thin formation of transition material is found between the clayey-silt and the marlstone layer, which is the third formation identified. Thickness along the section of the transition material layer varies from a couple of centimeters to a meter. Given the properties of this layer it was considered as part of the clayed-silt formation. Once the stratigraphy was defined, the soil parameters were then characterized. This was done by integrating results of the laboratory tests and CHTs. Figure 3 shows the mean shear wave velocity plus the maximum and minimum value obtained from CHT1.In the same plot are also depicted the values inputted in the numerical model for the deterministic analyses. The information coming from boreholes CHT1 and CHT2 (not reported in this paper) was then used to characterize the numerical 2D deterministic model in FLAC.

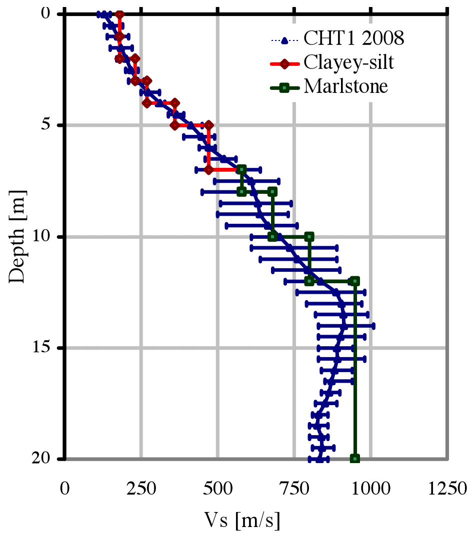

Fig. 3 Mean Vs value plus the maximum and minimum Vs readings obtained from CHT1 test. Also plotted in the figure are the values used as input for the deterministic analyses.

TWO-DIMENSIONAL DETERMINISTIC SITE RESPONSE ANALYSIS

A deterministic model is first analyzed using the software FLAC 2D. A nonlinear-visco-elastic constitutive model is used. Laboratory-derived shear modulus reduction curves were considered in order to take into account the soil nonlinear behaviour. The modulus reduction curves were converted into a sigmoid curve with three parameters in order to provide a continuous and differentiable expression as input parameter in the FLAC formulation. A low amount of Rayleigh viscous damping, 0.2 %, centered at a frequency of 5 Hz (close to the fundamental frequency of the system) has also been added to eliminate high frequency noise and to simulate energy losses of the soil undergoing low-strain cyclic excitations.

Creation of the Model

Grid definition. An adequate value for the spacing between nodes of the grid, h_{max}, depends on the minimum wavelength, λ_{min}, that propagates into a given element according to Equation (1), where Vs_{min} is the minimum shear wave velocity of the model, f_{max} is the maximum frequency of seismic excitation that one intends to propagate though the model and G is a parameter depending on the discretization method used, typically varying from 5 to 10. The section used in this study consists of a grid of 125 by 35 elements and the grid spacing h_{max} was calculated with Equation (1). Based on the above considerations, a value of 1m was finally chosen for both horizontal and vertical grid spacing (see Fig. 4).

$$h_{max} \leq \frac{1}{G}\left(\frac{Vs_{min}}{f_{max}}\right) = \frac{1}{G}\lambda_{min} \qquad (1)$$

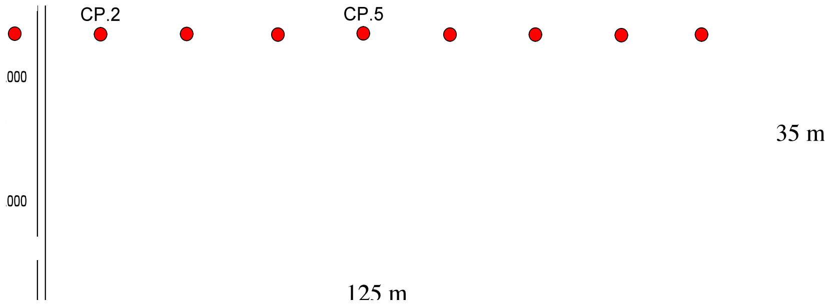

Fig. 4 Grid and control points along the surface of 2D section.

Boundary Conditions. Numerical methods relying on the discretization of a finite region of space require appropriate conditions to be enforced at the artificial numerical boundaries. At the bottom, a quiet boundary was assigned. For this purpose, the viscous boundary developed by Lysmer and Kunlemeyer [1969] implemented in FLAC 2D was used. Free field conditions were also assigned at both sides of the grid.

Seismic Input Motion. In FLAC 2D, the dynamic input can be applied at the bottom of the model in one of the following ways: a) acceleration time history, b) velocity time history, c) stress or pressure time history and d) force time history. For this study, a velocity time history was chosen as dynamic input.

Results

As described previously, a set of 7 spectrum compatible real records was selected for the UHS of the 475 years return period. The input motion #3 of such set was used to carry out 2D ground response analyses. Control points were set every 15 meters along the free surface of the section (see Fig. 4) in order to assess the variability of the response across it. The thickness of the superficial layer (clayey-silt) was considered uniform; as a result, for this study the lateral variability has no influence on the overall response. However, when slopping interfaces or irregular ground surfaces are present, the effects of lateral variability should be evaluated. The response spectrum was computed at control point 2 (CP 2). The acceleration response spectra illustrated in this study were calculated for 5% of structural damping.

Figure 5 a) shows the comparison between the acceleration response spectrum of the input motion used in the analysis before and after propagation. It can be noted how the PGA amplification is around 1.3. It is underlined that results shown in Fig. 5 a) were obtained using only one record from the selected set of input motions. However, one of the objectives of this study is to evaluate the influence of the variability of the input on the response. For this reason, 7 analyses were carried out using all the records of the selected set. Figure 5 b) shows the comparison between the UHS for the 475 years return period and the acceleration response spectrum of each of the records used in the analyses, obtained at CP 2. Also plotted in the same figure is the mean spectrum of the set. The amplification of the response occurring for all periods can be appreciated from this graph. It is also important to notice the difference between the spectrum obtained with input #1 and the rest of the set. A large amplification is obtained when propagating input #1. This is due to the frequency content of that particular record. In fact the record has a predominant frequency of about 5 Hz, which is about the same as the fundamental frequency of the site.

a) **b)**

Fig. 5 a) Comparison between the acceleration response spectrum of input motion 3 before and after propagation computed at CP 2; b) UHS and mean spectrum for the 475 years return period computed at CP 2 with the 7 records obtained at the free surface.

GEOSTATISTICS

Geostatistics is the application of random field theory to geosciences-related situations. The aim is to describe the spatial continuity of essential features on many natural phenomena by involving classical regression techniques [Isaaks and Shrivastava, 1989]. Thus, in a broader sense, GS is the statistics of regionalized correlated Random Variables (RV). It must be stressed that traditional stochastic geotechnical analyses generally assume independence between samples, while GS takes advantage of the fact that closely-spaced samples are often more correlated than those obtained at larger separation distances.

The procedure implemented in this work uses geostatistical interpolation of mechanical properties of the soil domain. The interpolation is based on field measurements of shear wave velocity data at specific locations. Monte Carlo Simulations are performed on the two-dimensional finite difference mesh to assess the variability of surface response, represented by the mean and standard deviation of the acceleration response spectra computed at several locations on top of the soil 2D section. The flow chart of the proposed methodology is illustrated in Fig. 6, for further details the interested reader may refer to [Alonso, 2008].

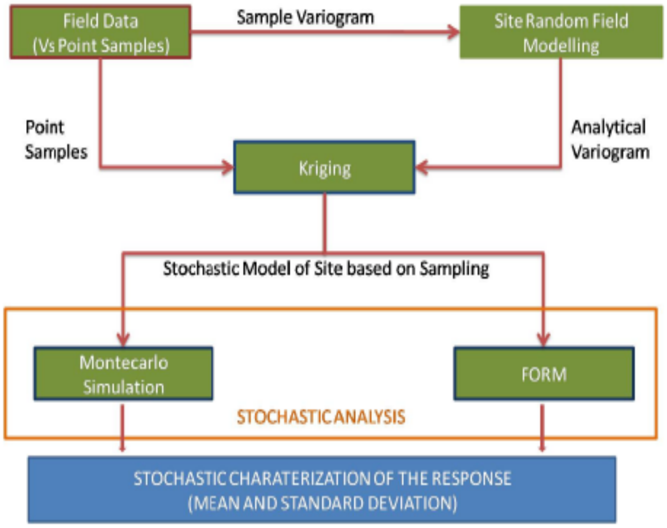

Fig. 6 Flow chart of the proposed methodology

Implementation

The statistical description was performed by considering the variogram approach, which describes indirectly the correlation between random variables comprised in a RF [Isaaks and Shrivastava, 1989]. The definition of the variogram involves the knowledge of several parameters, the most relevant being the sill and range, representative of variance and correlation among variables spatially spread. It was not possible to model the random field using only data from logs S-1, S-2 and S-3 (see Fig.1) due to their little statistical significance. Therefore, the shear wave velocity results of the 2D seismic tomography (Fig. 1 a) were used to characterize the variograms. Range on the horizontal direction was set equal to 125 m, implying that all points within this distance are horizontally correlated. This is a reasonable assumption for a homogeneously layered site. Range in the vertical direction was set equal to 4 m, corresponding to well defined layering scheme of a homogeneous material with variable properties. Ordinary Kriging [Isaaks and Shrivastava, 1989] has been performed on values of Vs at each borehole. Kriging is a group of geostatistical techniques to interpolate the values of a RF at an unobserved location, from observations at nearby locations, and constitute the simplest unbiased interpolation scheme on geostatistics. The results of Kriging and the position of the boreholes along the section are shown Fig. 7. The values of Vs estimated with Kriging were then used to compute the small strain shear modulus to be used in the 2D FLAC analysis. Figure 8 shows the values obtained and assigned to each element of the mesh generated for the 2D section.

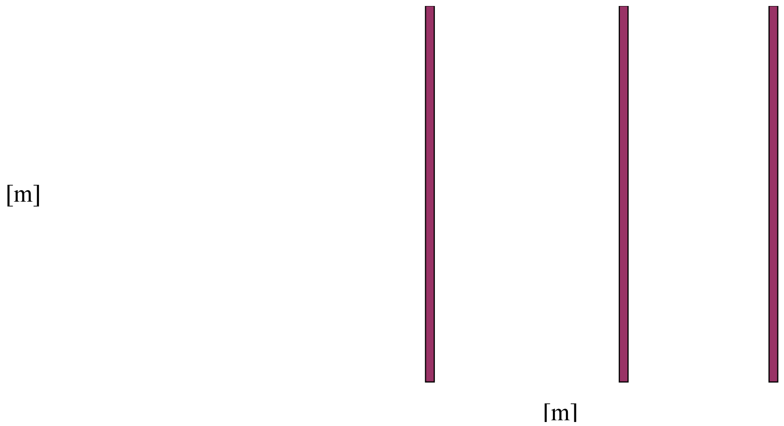

Fig. 7 Position of Boreholes S-1, S-2 and S-3 and shear wave velocity (Vs) values [m/s]obtained along the 2D section using Geostatistics.

Figure 9 shows the computed standard deviation of shear wave velocity estimates. The darker zones represent small values of standard deviation. In fact, these are overlapped with the position of the boreholes used to perform geotechnical characterization. It is observed that CP 2 is located over a region where standard deviation values are larger, since it is far away from the borehole. CP 5 is instead located between two boreholes: as a result, predicted values of shear wave velocity have a smaller dispersion. This aspect is an obvious and direct consequence of the fact that the validity of the variogram decreases with the distance from the known values of the random variables.

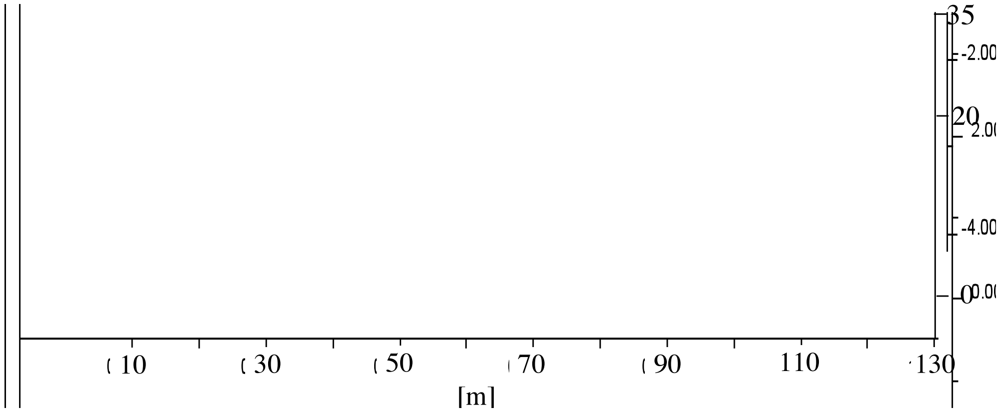

Fig. 8 Small-strain shear modulus field assigned to the mesh generated for 2D section with the GS approach. Values of shear modulus expressed in Pa.

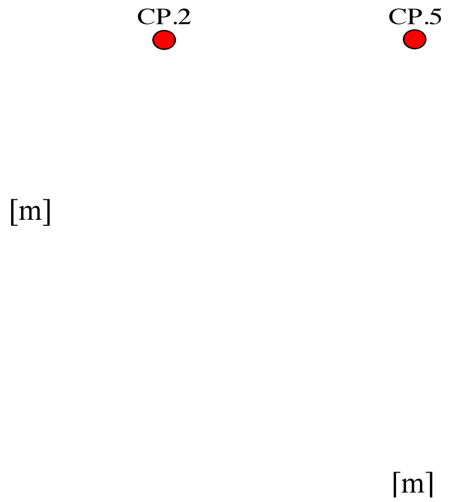

Fig. 9 Standard deviations of Vs [m/s] and position of control points 2 and 5.

As for in the deterministic study, two cases were taken into account. One only considers the variation in the geotechnical properties; the other also addresses the record-to-record variability. For the first part, 100 realizations of small strain shear modulus were generated, using MCS and Kriging. A MATLAB [The MathWorks, 2007] function was generated for this purpose. Each realization was then assigned to a grid mesh to carry out the site response analysis using FLAC 2D. Record #3 of the selected set was again used as input motion for all the 100 analyses. In this way it is possible to assess the influence of the variability of soil parameters. The response spectrum for each of the 100 simulations was computed at control point CP 2. Figure 10 shows the comparison between the acceleration response spectra of the input motion #3 and the mean spectrum of the 100 accelerations computed at the free surface. Also plotted in the same figure is the scatter of the response. It is noted that the standard deviation of the acceleration response spectra computed at the free surface is relatively low. This implies that, for this study, the influence of the variability of soil parameters on the results of site response analysis is small. Furthermore the amplification found with the site-effect amplification obtained with GS is smaller that the amplification computed with the deterministic model. This becomes clearer in Fig. 11 a). The figure shows the comparison between the mean response spectrum from the GS methodology and the result obtained with the deterministic model. The spectral acceleration computed at zero period in the deterministic case is 1.3 m/s^2, while the mean value computed with the implementation of the stochastic methodology is 1.5 m/s^2.

Fig. 10 Comparison of the acceleration response spectra of input motion #3 and mean acceleration spectrum of the response computed at free surface in CP 2 using 100 realizations of low strain shear modulus based on Kriging. The red area represents the mean plus and minus two standard deviations.

Figure 11 a) and b) show the mean response computed at CP 2 and CP 5, compared with the results from the deterministic model. For all spectral periods, the amplification obtained with the stochastic approach is slightly larger than the one obtained with the deterministic case. Another important aspect to consider is the effect of lateral variability. It can be noted the higher amplification at CP 5, which is closer to the layering discontinuity noticeable in Fig. 8. This is an indirect confirmation of the validity of the numerical analyses, which give results accordingly to the expectations.

a) **b)**

Fig. 11 a) Mean response spectra from GS methodology and results of deterministic model computed at CP 2; b) mean response spectra from GS methodology and results of deterministic model computed at CP 5.

Since the larger amplification occurs at CP 5, in the following considerations the comparison will be made only at this location. The second set of simulations evaluates the influence of the input motion variability on the overall response. This was achieved by means of 100 FLAC 2D site response analyses in which different input motions were used. 100 realizations of shear wave velocity were generated using GS. Each realization was then mapped to a grid mesh to be analyzed in FLAC 2D. The entire set of 7 selected records for the 475 years return period was used to perform site response analysis. The set of input records was described with a uniform probabilistic distribution. This implies that every time an analysis is carried out, a record is randomly chosen from the set, with every record having the same probability of being selected. In this way the randomness of the seismic input is taken into consideration.

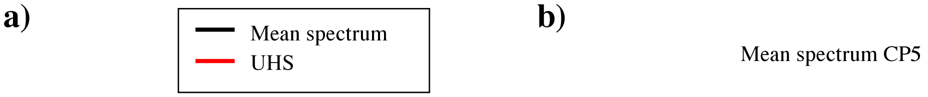

Fig. 12 a) UHS and mean spectrum for the 475 years return period computed at CP 5 with the 100 acceleration obtained at the free surface, based on Kriging; b) UHS and mean acceleration spectrum at the free surface for Tr= 475 years computed at CP 5 with the associated uncertainty. The red area represents the mean plus and minus two standard deviations.

Figure 12 a) shows the acceleration response spectra computed at CP 5 with the accelerations obtained at the free surface. Also plotted in the same figure is the comparison between the mean spectrum of the 100 analyses and the UHS for the 475 years return period. The influence of the variability of the input motion can be seen. This becomes more evident in Fig. 12 b), where a comparison is made between the UHS and the mean spectrum at control point CP 5, which is plotted together with plus/minus two standard deviations in order to illustrate the variability of the response.

RANDOM FIELD THEORY

A variety of different methods of generating realizations of random field exists, principally the spectral method, the matrix decomposition method, the turning bands method, and the screening sequential simulation method [Fang and Tacher, 2003]. Among them, the matrix decomposition (MD) method is simple to implement in practice. Furthermore, the method has the advantage of allowing fields of irregular geometry without additional computational effort. The MD method essentially involves the construction of the covariance matrix of the random field and its subsequent Cholesky decomposition into an upper and lower triangular matrix. The lower triangular matrix is then multiplied by a vector of uncorrelated standard Gaussian variables, producing a stochastic field possessing the prescribed covariance function. It is recognized that the covariance function serves as an input quantity in the model. The accuracy of the method is expected to be high due to the fact that the generation accounts for all possible nodal correlation values. However, a practical limit on the number of nodes emerges because of the Cholesky decomposition and the storage of the matrix. Another advantage of the method is that the matrix decomposition step needs only to be performed once for Monte Carlo simulations, because only backward substitution is required to generate each additional realization.

In this study, the MD method was implemented to generate Non-Gaussian correlated RFs of low strain shear modulus. Autocorrelation distances of 125 m and 4 m were considered in the horizontal and vertical direction respectively for compatibility with Geostatistics. RFs were generated for each material and then mapped to a mesh grid to perform site response analyses with FLAC 2D. A MATLAB function was generated for this purpose.

Implementation

Table 2 shows the mean, the CoVs, and the distribution type assumed to generate the RFs. The CoV and the distribution type were taken from the PEER report by Jones *et al.* [2002].

Table 1 Assumed input parameter uncertainty.

Property	Mean	CoV (%)	Distribution
G_{max} Layer 1 [Pa]	126E6	12	Lognormal
G_{max} Layer 2 [Pa]	441E6	12	Lognormal

Two indices of correlation, namely the scale of fluctuation and the autocorrelation distance, have been used to describe the spatial extent within which soil properties show a strong correlation. The autocorrelation distance is defined as the distance to which the autocorrelation function decays to 1/e, where e is the base of the natural logarithm. The scale of fluctuation is defined as:

$$\delta = \int_{-\infty}^{\infty} \rho(\eta)\, d\eta \tag{2}$$

where $\rho(\eta)$ is the autocorrelation function and η is the separation of two points. For the exponential autocorrelation function, the scale of fluctuation is two times the autocorrelation distance. A Gaussian RF is completely defined by its mean μ (x), variance σ^2 (x), and autocorrelation function ρ (x,x'). Autocorrelation functions commonly used in geotechnical engineering have been presented by Li and Lumb [1987] and Rackwitz [2000]. In this study, an exponential autocorrelation function is used and different autocorrelation distances in the vertical and horizontal directions have been assumed as follows:

$$\rho(x,y) = \exp\left[-\frac{|x-x'|}{l_h} - \frac{|y-y'|}{l_v}\right] \tag{3}$$

where l_h and l_v are the autocorrelation distances in the horizontal and vertical directions, respectively. The values of l_h and l_v were assumed as 125 and 4 meters. The shear modulus is herein considered as a RF with a lognormal distribution. The lognormally distributed RF is therefore obtained by:

$$H(x_i) = \exp\left[\mu_{\ln}(x) + \sigma_{\ln}(x) \cdot G_i(x)\right] \tag{4}$$

The values of $\mu_{\ln}$ and $\sigma_{\ln}$ are determined using a lognormal transformation that was carried out following the procedure presented by Haldar *et al.* [2007].

$$\sigma^2_{\ln} = \ln\left(1+\frac{\sigma^2}{\mu^2}\right) = \ln\left(1+\mathrm{CoV}^2\right) \tag{5}$$

$$\mu_{\ln} = \ln\mu + \frac{1}{2}\sigma^2{}_{\ln} \tag{6}$$

$G_i(x)$ is a vector coming from the multiplication of the decomposed correlation matrix and a sequence of independent standard normal RVs (with zero mean and unit standard deviation). By performing MCS on these RVs, it is possible to generate a number of realizations of RFs. The process is repeated 100 times. A RF is generated for each considered layer. A suitable mapping was then performed in order to assign to each of the FLAC zone, a value of the shear modulus coming from the implemented RFs. Further details on this process can be found in [Sanchez, 2010]. One of the 100 realizations of shear modulus distribution obtained for the 2D model is illustrated in Fig. 13.

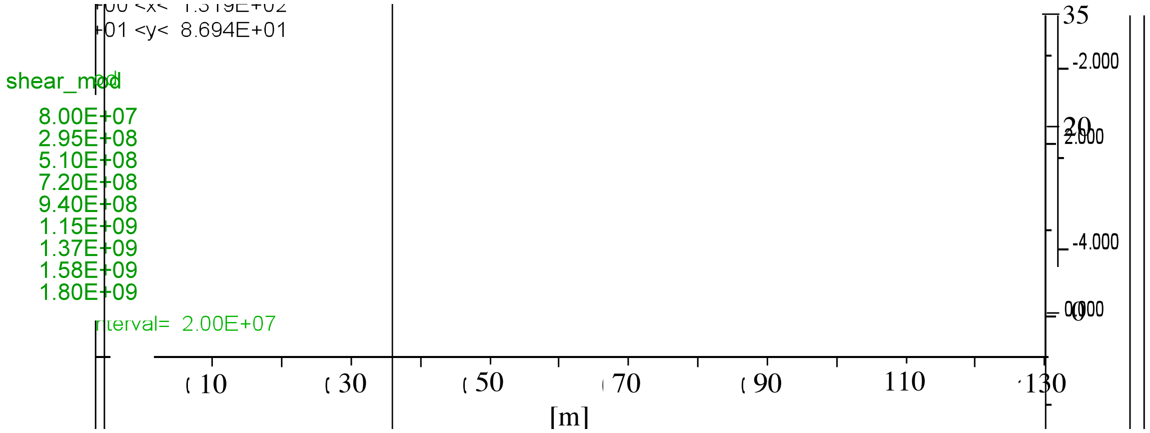

Fig. 13 Realization of Non-Gaussian random field of small-strain shear modulus (values expressed in Pa). A RF was generated for each layer considered. Correlation distance assumed in the vertical and horizontal direction: 4 m and 125 m.

Figure 14 shows the results of the analyses performed on all the RFs realizations subjected only to the ground motion #3. Also in this case the amplification coming from the statistical model is larger than the one obtained with the deterministic model. Comparing Fig. 14 b) and Fig. 11 b), it can also be observed that there is a higher amplification computed with the RF method. This is due to the fact that the RF approach does not perform any interpolation on the data. On the other hand, the implemented GS method, based on Kriging, interpolates between the known assigned test data. For this reason, RF approaches are also regarded as "unconditional", while Kriging is referred to as "conditional" [Lee and Ellis, 1997]. Loosely speaking, the difference can be also interpreted considering that the RF does not account for boundary conditions in the same way as Kriging does. This also indicates a better suitability of RF to model cases where there is a poor geotechnical characterization, while Kriging may be more indicated when detailed geotechnical data are available.

Figure 15 a) shows the acceleration response spectra computed at CP 5 with the accelerations obtained at the free surface, based on RF. Also plotted in the same figure is the comparison between the mean spectrum of the 100 analyses and the UHS for the 475 years return period. Again, the very important influence of the variability of the input motion can be seen. Figure 15 b) reports a comparison between the UHS and the mean spectrum at control point CP 5, which is plotted together with plus/minus two standard deviations in order to illustrate the variability of the response. By comparing this graph with the analogous Fig. 12 b), obtained with the GS-Kriging approach, it is noted a larger dispersion resulting from the RF method. However, the mean spectrum remains approximately the same for both cases. It is also noted that the higher standard deviation obtained with RF approach may also be due to more simulations from record #1 (compare Fig. 12 a) with Fig. 15 a)). Overall, it can be stated that GS-Kriging and RF simulations results in very similar amplifications.

a) **b)**

Fig. 14 a) Comparison of the acceleration response spectra of input motion #3 and mean acceleration spectrum of the response computed at free surface in CP 5 utilizing 100 realizations of low strain shear modulus, based on RF. The red area represents the mean plus and minus two standard deviations; b) Mean response spectra from RF methodology and results of deterministic model computed at CP 5.

a)

— Mean spectrum
— UHS

b)

Mean spectrum CP5

Fig. 15 a) UHS and mean spectrum for the 475 years return period computed at CP 5 with the 100 acceleration time histories obtained at the free surface, based on RF; b) UHS and mean acceleration spectrum at the free surface for Tr= 475 years computed at CP 5 with the associated uncertainty. The red area represents the mean plus and minus two standard deviations.

The above consideration is also clearly shown in Fig. 16. The graph illustrates the amplification ratio at all spectral period resulting from the different modeling options. The ratio is always computed between the mean spectrum at CP 5 (100 simulations with randomly assigned low-strain shear modulus, and randomly assigned ground motion of the set) and the UHS at bedrock for the 475 return period. The amplifications obtained considering the randomness in the shear wave velocity profiles are larger than the one coming from the deterministic model at all spectral ordinates. Again, similar amplifications are obtained with the GS-Kriging and RF methods.

Fig. 16 Amplification ratio at CP 5 from the different modeling options. The ratio is calculated between the mean spectrum based on 100 realizations and the UHS for 475 years return period.

CONCLUSIONS

The work illustrates and compares the results of 2D fully stochastic site response analyses using two approaches: GS-Kriging and RF. The two methods have been consistently implemented, using the same vertical and horizontal correlation distances. The amplifications obtained with both methods are larger than the one coming from the deterministic analyses. For the considered case-study, the stochastic methods give comparable results. It has to be considered, however, that GS-Kriging may be more useful in cases where detailed measurements are available, while the RF may be more conveniently adopted when the geotechnical characterization is scarce. This is due to the fact that GS-Kriging performs interpolations on known conditions, such as bore-holes data, while RF cannot consider specific measurements. When assessing the relative suitability of the two methods, it is also important to recognize that the numerical simulations involved with GS-Kriging are significantly faster than the realizations of the RFs. In fact, the generation of the RFs and the subsequent mapping for assigning the values into the FLAC grid, required approximately twice computational time than the GS-Kriging interpolations. It can be concluded that, for the specific case study addressed in this paper, due to the large amount of experimental data available, GS-Kriging appears to be the more suitable approach.

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