Evaluating the effects of the spatially variable shear-wave velocity on seismic site response

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ABSTRACT

The spatial variabilities of soil properties play an important role in geotechnical engineering. The site effects are typically assessed by 1D site response analysis, which cannot account for the lateral variabilities of soil properties. To address such limitation, 2D site response analyses were performed using 2D randomized shear wave velocity profiles. The spatially variable shear wave velocities in the 2D soil model were first simulated by random field theory under different coefficients of variation (COVs) and correlation lengths (CLs). Then, 2D and 1D site response analyses using the 1D soil column selected from the 2D soil model were performed for comparison. The results revealed that the mean ground response spectra of the 2D variable soil profiles were smaller than those of the lateral homogeneous or 1D soil profiles. Such effect can be simply considered in the 1D analysis but with a large damping depending on the COV and CL of the soil profiles.

Keywords: Site response analysis; spatial variability; correlation length; shear-wave velocity

1 INTRODUCTION

Predicting the influence of local soil conditions on expected earthquake ground motions is a critical aspect of seismic design. In many situations, the effects of soils conditions on ground shaking are assessed through seismic site response analysis, which are dynamic simulations of wave propagation. This analysis propagates rock acceleration–time histories through the 1D soil profile to compute the acceleration–time histories on the ground surface. However, this procedure disregards the variabilities of soil properties in the lateral space that is widely recognized.

To address such limitation, 2D site response analyses were performed using 2D randomized shear wave velocity (Vs) profiles in this study. The spatially variable shear wave velocities in the 2D soil model were first simulated by random field theory. Then, the 2D and the 1D site response analyses using 1D soil column selected from the 2D soil model were performed for comparison. The mean ground response spectra of the 2D variable soil profiles were compared with those of the lateral homogeneous or 1D soil profiles.

2 SPATIALLY VARIABLE PROPERTIES

The spatial variability of geotechnical profiles can be quantified by using several statistical parameters, such as central trend (or mean), coefficient of variation (COV), correlation length (CL), and anisotropy (Vanmarcke, 1977). For example, the spatial variation in geotechnical property X with depth z can be decomposed into a trend function μ and a fluctuating component w (Fig. 1):

$$X(z)=\mu(z)+w(z) \quad (1)$$

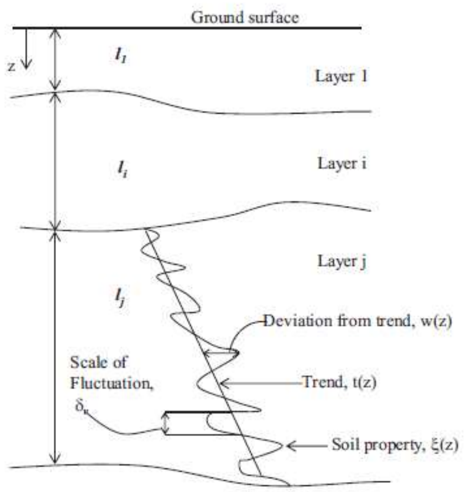

Fig. 1. Inherent soil variability (reference)

The standard deviation σ(z) of the inherent spatial variability for a statistically homogeneous variability function w(z) normalized by the local mean geotechnical property μ(z) obtained from the trend function provides a useful dimensionless ratio known as

$$COV(z)=\sigma(z)/\mu(z) \quad (2)$$

The scale of geotechnical property fluctuation is an important spatial characteristic of the ground that indicates the distance scales within the material properties that show strong spatial correlations. A parameter with a short scale of fluctuation rapidly changes with position, whereas a parameter with a long scale of fluctuation changes over greater distances. The scale of fluctuations in geotechnical fields can be described by using correlation lengths in covariance functions. The correlation length (i.e., autocorrelation length) is the distance at which spatial autocorrelations decay by 1/e, which is approximately 37% (DeGroot and Baecher, 1993). The scale of fluctuations is generally between 1.4 and 2.0 times the CL for exponential, squared exponential, and spherical autocorrelation functions (Vanmarcke, 1983).

3 SIMULATION OF VS PROFILE

Given the specified correlation model as described in Section 2, the sample data with such a correlation structure can be simulated. Various spatial random field generation techniques have been introduced, such as matrix decomposition method, local area subdivision method, spectral method, FFT, and neural network approach. In this study, a sequential approach (Chen et al., 2012) was adopted.

A sequential approach for the simulation procedure involves simulating each value individually depending on all previously simulated values. The first step in the sequential simulation process is to generate a single realization of a standard normal variable. All subsequent realizations are then dependent on all previous realizations, all of which are represented by the joint distribution

$$\begin{bmatrix} Z_n \\ Z_p \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_n^2 & \Sigma_{np} \\ \Sigma_{pn} & \Sigma_{pp} \end{bmatrix}\right) \quad (3)$$

where ~N($\boldsymbol{l}$, **R**) denotes that the vector of random variables has a joint normal distribution with mean vector $\boldsymbol{l}$ and covariance matrix **R**, $\mathbf{Z}_n$ is the next realization to be simulated, and $\mathbf{Z}_p$ is the vector of all previously defined or simulated points. The mean vector and the covariance matrix were partitioned to clarify several equations. Subscripts n and p in the partitions represent “next” (as in next point to be simulated) and “previous” (as in all previously simulated points), respectively. The individual terms inside the covariance matrix are defined by

$$\mathrm{COV}[Z_t, Z_j] = \rho_{Z_i,Z_j} \cdot \sigma_{Z_i} \cdot \sigma_{Z_j} \quad (4)$$

where Z_i and Z_j refer to two locations within the random field at any scale with standard deviations σ_{Zi} and σ_{Zj}, respectively, and $\rho_{Zi,Zj}$ is the correlation coefficient between them. Given the above model, the conditional distribution of the next realization to be simulated is given by a univariate normal distribution with an updated mean and variance

$$(Z_n|Z_p = z) \sim N(\Sigma_{np} \cdot \Sigma_{pp}^{-1} \cdot z, \sigma^2 - \Sigma_{np} \cdot \Sigma_{pp}^{-1} \cdot \Sigma_{pn}) \quad (5)$$

Once simulated, $\mathbf{Z}_n$ becomes a fixed data point in vector $\mathbf{Z}_p$ to be conditioned upon by all subsequent realizations. This process is repeated until all values in the field have been simulated. Fig. 2 shows a sample simulation by random field.

4 ANALYSIS CASES

Two soil layer systems with mean Vs of 150 and 300 m (15 m thick each) were selected as base models. All soil layers were assumed to have 5% damping and a unit weight of 17 kN/m^3. The 2D randomized profiles with the horizontal dimension of 100 m were generated by the procedure mentioned in the previous section. The dimensions of each element were 1 m by 1 m. Different COVs (10%, 20%, and 30%) and CLs (5, 10, and 20 m) were considered for the parametric analysis. Fig. 2 shows an example of six realizations with different COVs and CLs. As the COV increased given a constant CL (Fig. 2 left column), a large variation was observed, whereas a CL increase given a constant COV (Fig. 2 right column) resulted in less variation (i.e., Vs profiles were more uniform).

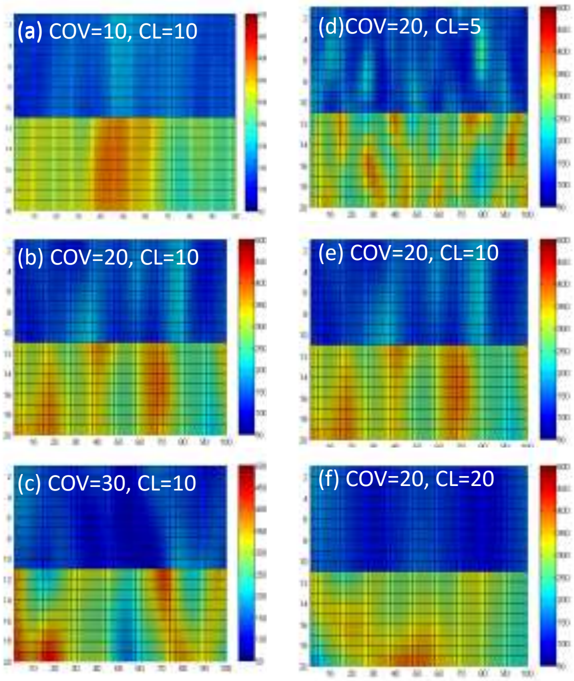

Fig. 2. Simulated Vs profile with different COVs (left column) and CLs (right column).

The bottom of model was fixed as the rigid base, and both sides were applied with free field boundary. 2D analysis with the generated profiles were performed using the FLAC program. The ground motion recorded during the Chi-Chi earthquake was selected as input motions. The horizontal motion was vertically propagated through the soil model and, the surface motions at all locations were reported.

In addition to the 2D analysis, the 1D site response analysis using the 1D soil column selected from the 2D soil model was performed. The surface motions at the same location obtained by 1D and 2D analyses were also compared.

5 ANALYSIS RESULT

Fig. 3 shows the response spectra at different locations (with the left point as the reference, i.e., 0 m). The surface responses varied at different locations. Compared with the reference point, the variation of response increased as the separation distance increased. The lowest response occurred in the center of the model, and the others increased gradually toward the boundary. Most of the 2D responses were lower than the response from the base model. Thus, the mean response spectra of all locations were lower than that of the base model (Fig. 4). These results indicated that the variation of the Vs profile lead to the lower surface response compared with that obtained by the typical 1D analysis that did not consider the lateral variation.

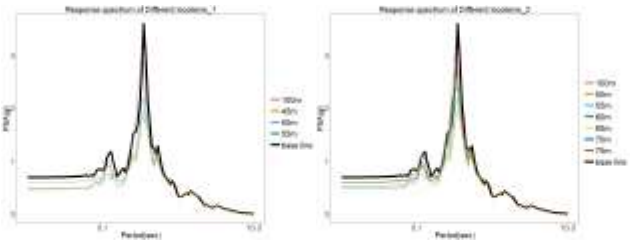

Fig. 3. Response spectrum of different locations (COV=20 CL=10)

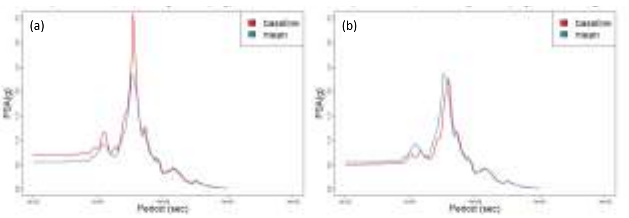

Fig. 4. Mean response spectrum of 2D analysis and response spectrum of baseline case (5% and 8% damping)

The response spectra of the 2D and 1D site response analyses were further compared at the same locations, as depicted in Fig. 2. In the 1D case, the variation of the Vs profile in the vertical direction was considered, whereas that in the horizontal direction was neglected. Fig. 5 shows that the 2D result was lower than the 1D result at the same location except for at the boundary. The similar responses of the 1D and 2D analyses at the boundary were due to the free field boundary used at this location that was essential to the 1D analysis. The results for the center of models indicated that the 1D analysis are more conservative. The variation of the Vs profile in the horizontal direction leads to the lower surface response. The reason is that the inhomogeneous profiles cause additional energy dissipation during the wave propagation. Therefore, to simply consider the lateral variation in the 1D analysis, additional damping can be added in the 1D analysis. Fig. 5b shows that the 1D analysis with 8% damping can closely match the 2D analysis with 5% damping.

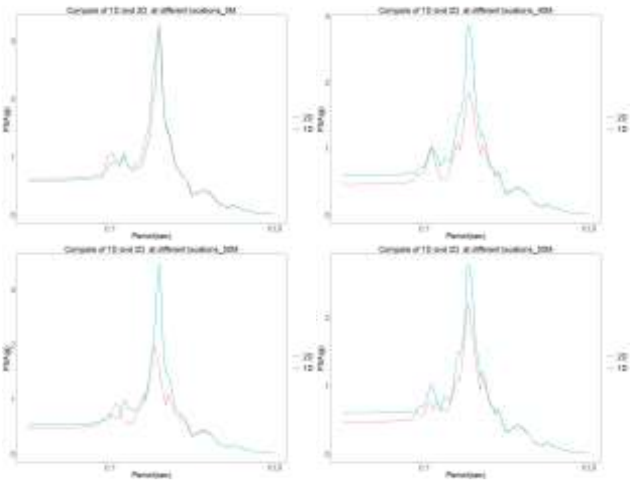

Fig. 5. Comparison of 1D and 2D analysis result at different locations

The influences of COV and CL were further evaluated in Fig. 6 and Fig. 7. Fig. 6 compares the mean response spectra, and Fig. 7 shows the associated standard deviations against the periods. As the COV increased (Fig. 6a and 6a), both the means spectrum and the standard variation increased, particularly at the site period of 0.2 s. The high COV indicated the high variation of the soil profiles, which resulted in a higher standard deviation. However, more inhomogeneous profiles (i.e., higher COV) caused more interference and energy dissipation during the wave propagation. Thus, a lower mean spectrum was expected. The reason that the analysis result is different from the expectation is because this is based on one realization. As more analyses were performed, the mean spectrum should decrease as the COV increased in general.

By contrast, the different CLs led to the similar mean spectrum and standard deviation (Fig. 6b and 6b). Compared with the COV, the CL exerted less influence on the response. The reason is that the mean spectrum was the average of response at all locations and cannot reflect the spatial variation induced by CL provided that the model was wide enough. To emphasize the role of CL, other methods for evaluating the influence of CL should be developed.

In general, the mean response was lower than the baseline case regardless of the COV and the CL. Additional damping can be added to the base model to consider the variation of the Vs profile for the mean responses. However, although the mean response was reduced, the mean+one standard deviation response increased with the COV and was sometimes even higher than that of the baseline model (Fig. 8). The high mean+one response spectrum should be considered instead of the mean if the inhomogeneous profiles are considered.

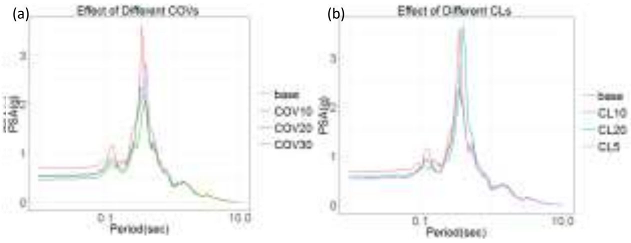

Fig. 6. Comparison of mean spectrum for different (a) COVs and (b) CLs

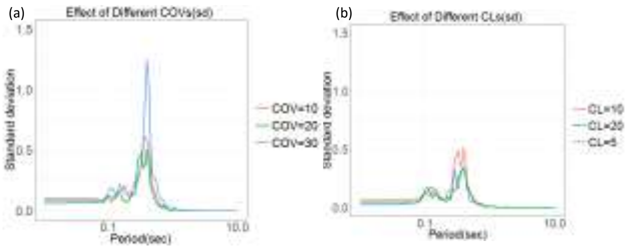

Fig. 7. Comparison of standard deviation of different (a) COVs and (b) CLs

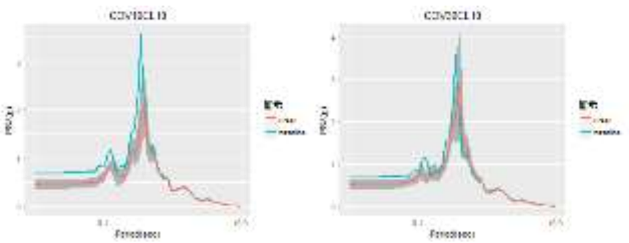

Fig. 8. Comparison of response spectrum of baseline case and different randomized case

6 CONCLUSIONS

2D site response analyses are performed using 2D randomized shear wave velocity profiles to evaluate the influences of inhomogeneous profiles on site responses. The spatially variable shear wave velocities in the 2D soil model were simulated by random field theory under different COVs and CLs. The results revealed that the mean ground response spectra of the 2D variable soil profiles were smaller than those of the lateral homogeneous or 1D soil profiles. Such an effect can be simply considered in the 1D analysis but with a large damping depending on the COV and CL of the soil profiles. However, although the mean response was reduced, the mean+one standard deviation response was sometimes even higher than that of the baseline model. The high mean+one response spectrum should be considered instead of the mean if the inhomogeneous profiles are considered.

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Acknowledgements should be written here.

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