Effects of Variability in Base Excitation on the Response of Liquefiable Heterogeneous Sloping Ground

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ABSTRACT

The results of a series of nonlinear finite element simulations are presented to demonstrate the effects of base motion variability on liquefaction-induced lateral spreading of mildly sloping grounds. The analyses are part of the 2017 Liquefaction Experiments and Analysis Project (LEAP-2017). A key objective of LEAP is to generate a database of reliable centrifuge experiments to facilitate the validation of the current state-of-the-art analysis tools for the modeling of soil liquefaction. In the context of centrifuge experiments, the sources of uncertainty in the base motion are the magnitude and frequency content differences between the target and the achieved base motions. While centrifuge experiments are conducted with diligence, achieving the target base motion is restricted by the machine limitation and the presence of noise. A series of Monte Carlo (MC) simulations are performed to investigate the effects of the base motion variability. Base motion statistics are obtained as a function of frequency capturing the variations observed in the spectral accelerations of the achieved base motions. The simulations presented in this paper consider the cases of homogeneous soil as well as spatially variable soil conditions. The results of the MC simulations are used to shed light on how small deviations of the achieved base motion from the target motion might influence the response of liquefiable ground. Sensitivity of the computed soil responses to these deviations are assessed by considering the variations of excess pore pressures, lateral spreading, and ground surface settlements.

INTRODUCTION

The Liquefaction Experiments and Analysis Project (LEAP) is an international multi-institution initiative to develop a database of high quality centrifuge experiments that can be used for further development and validation of numerical analysis tools. To realize this objective a deeper understanding of the sources of variability in the centrifuge experiments is necessary. A thorough investigation of the effects of variability using physical experiments is a formidable task as it is expensive and time consuming to perform the large number of experiments required for a meaningful statistical analysis. Moreover, it is difficult to isolate the sources of variability in order to study their effects separately. An alternative and perhaps more viable approach is the use of Monte Carlo (MC) simulations that utilize a well-tested numerical modeling platform. In this approach, a series of fully-coupled nonlinear finite element simulations can be conducted while controlling the varying parameters.

The sources of variability that may affect the response of the soil are various. The variations in the achieved soil density and input motion are identified as the most influential sources for the problem at hand. Soil density as a property of the soil is treated as a spatially variable random field. On the other hand, the variability in the input motion is treated as a non-stationary random process. The work reported here is an extension of the authors' previous work that mainly focused on investigating the effects of spatial variability of soil density on the seismic response of liquefiable sloping ground (ElGhoraiby et al. 2017; ElGhoraiby and Manzari 2017). The objective of this paper is to study the effects of variability in the achieved base motions.

The variability in the base motion can be attributed to various causes depending on the application. In the field, strong-motion recordings are influenced by soil characteristics, fault type, and distance from the source among others. In the laboratory, the target base motion is predetermined but the achieved base motions almost always vary with respect to the target motion. These variations are usually affected by the effectiveness of the control system, stiffness of the container box, dynamic characteristics of the centrifuge, and many other factors. This variability is manifested in the variations of the amplitude and the frequency content of the resulting motion.

The effects of spatial variability of soil properties and the uncertainties in the base motion have been studied in many recent investigations including site response analysis (Lopez-Caballero and Modaressi-Farahmand-Razavi, 2010; Popescu et al. 2005; Rathje et al. 2010; Sen 2012), liquefaction-induced lateral spreading (Montgomery and Boulanger, 2017; ElGhoraiby and Manzari, 2017), seismic response of dams (Gazetas et al., 1981; Boulanger and Montgomery, 2016) and seepage beneath water retaining structures (Griffiths and Fenton, 1993) among others.

While majority of the work reported in literature focused on studying the effects of spatial variability of soil properties using random finite element method (RFEM), the effects of base motion variability have also been studied in a few geotechnical applications. For example, Gazetas et al. (1981) studied the effects of base motion variability on the response of earth dams. Synthetic base motion was modeled using Kanai-Tajimi power spectral density function and an arbitrary variation in intensity with time. Rathje et al. (2010) investigated the influence of base motion variability on the site response using the equivalent-linear approach. They also considered the variability of shear-wave velocity profile of the site. Rathje et al. (2010) and Sen (2012) selected multiple suites of input motions to fit the same target acceleration response spectrum.

Popescu et al. (2005) investigated the effects of the spatial variation of the soil cone tip resistance, q_n, on the soil liquefaction. Ground motion time histories matching the uniform building code recommended type 1 response spectrum were generated for the analyses. Boulanger and Montgomery (2016) modeled the soil spatial variability based on available standard penetration test (SPT) results. The seismic response of an embankment dam was investigated. Selected base motion was scaled to different PGAs and used to obtain the fragility cruves of the maximum lateral displacement. Montgomery and Boulanger (2017) investigated the effects of spatial varaiability on the liquefaction-induced lateral spreading of a multi-layered sloping ground. Lopez-Caballero and Modaressi-Farahmand-Razavi (2010) studied the combined effects of base motion variability and soil spatial variability on the response of liquefiable soils. Synthetic base motions were generated for the MC simulation. Spatial variability of the soil was modeled based on the variability in shear modulus degradation, damping and liquefaction strength curves of the soil. The effects of different spatial correlation lengths on the variability of soil parameters and their consequences were considered. The study suggested that the soil response is more sensitive to base motion variability than spatial variability.

The focus of this paper is to investigate the effects of variation in the base motions achieved in the course of LEAP-2015 and LEAP-2017 centrifuge experiments on the response of a mildly sloping liquefiable soil. Statistics of the response spectra of the achieved base motions (Kutter et al. 2017) are used here to generate realizations of synthetic base motions for the Monte Carlo simulations. Two different cases were considered: homogeneous and heterogeneous soil conditions. The variability of soil response in terms of displacements and excess pore water pressures are obtained and analyzed for each case. Observations regarding the probability distributions of permanent displacements at different locations on the soil surface are presented. In the following sections, first the main elements of the experiments and the assumptions considered in the stochastic analyses are discussed. The results of MC simulations are then presented along with discussion of the observations deduced from them.

LEAP CENTRIFUGE EXPERIMENT

The 2015 and 2017 LEAP projects investigated the response of mildly sloping liquefiable ground and the sensitivity of this response to the variation of soil relative density and base motion. The centrifuge specimen (Figure 1) is composed of a single layer of Ottawa F65 sand with a slope of 5-degrees. The slope has a height at mid-distance of 4.0 meters, a length of 20 meters and a width of at least 9.0 meters (depending on the centrifuge facilities) in the prototype scale. The specimens are constructed in a rigid box. The target soil density is 1652 kg/m^3 and the target base motion is a ramped sinusoidal motion with a PGA of 0.15g and frequency of 1 Hz. The instrumentation includes three arrays of pore pressure transducers and accelerometers at the center as well as at 3.5 meters away from the walls of the rigid box (Figure 1). Additional information about the experimental setup can be found in Kutter et al. (2017). Centrifuge facilities in the US, UK, Japan, Taiwan, China, Korea, and France performed similar experiments. While all the experiments shared the same prototype specifications they varied in model scale and centrifugal acceleration to accommodate the limitations and capabilities of each centrifuge facility. Additionally depending on the direction of the shaking (parallel or perpendicular to the axis of rotation), the top surface of the soil specimen was curved to account for the effects of centrifugal acceleration on the soil.

The experiments exhibited variability in the achieved soil density and base motions. Figure 2 shows the range of acceleration response spectra calculated for the base motions achieved in the 15 centrifuge experiments performed during LEAP-2017 project at 9 different centrifuge facilities. The mean spectrum and the spectra corresponding to the mean +/- one standard deviation are also shown. While the target base motion had a frequency of 1 Hz, the achieved base motions had higher frequency content participation. It is also noted that while the target peak ground acceleration was 0.15g, the achieved peak ground acceleration (PGA) had a mean value of 0.176 g and a coefficient of variation of 14.4 %. The maximum range of variation in the achieved soil density was +/- 54 kg/m^3 as it was reported by the participating centrifuge facilities (Kutter et al., 2017).

STOCHASTIC ANALYSIS SETUP

Figure 2 shows the variations observed in the base motions achieved in the LEAP-2015 and LEAP-2017 centrifuge experiments. Here the base motion was treated as a random process defined by the mean response spectrum (shown in red) and the covariance matrix of the spectral acceleration of the achieved base motions. For MC simulations, random response spectra were generated using the obtained mean and covariance. Once a random response spectrum was obtained, a corresponding time history base motion was generated iteratively.

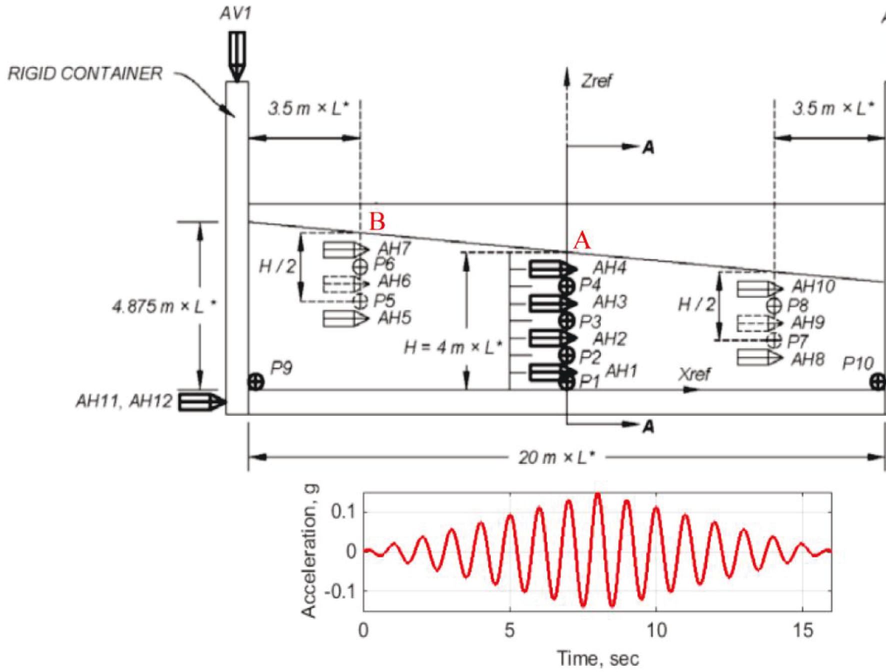

Figure 1. LEAP-2015 and 2017 test configuration and target base motion

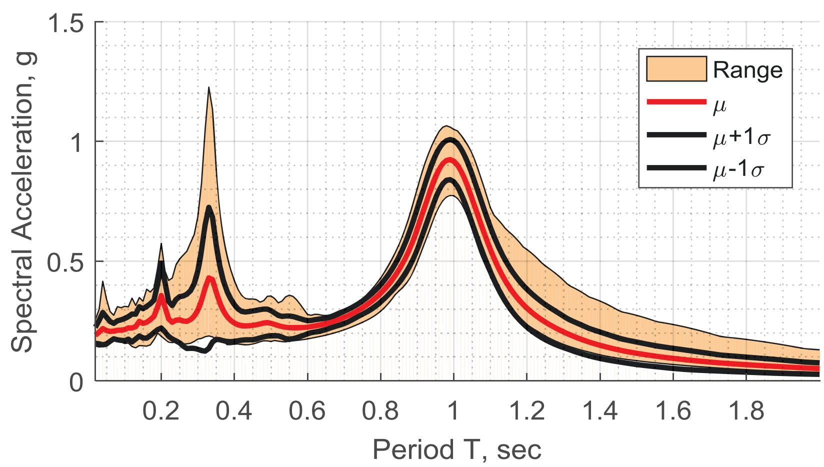

Figure 2. Spectral acceleration of the achieved base motions in LEAP-2015 and 2017 tests (Damping ratio = 5%).

The generated time history consisted of a set of ramped sinusoidal waves with a frequency in the range of 0.01 to 50 HZ covering the range of the frequencies in the response spectra. The peak amplitude of each wave was obtained iteratively to match the generated response spectrum. The phase angle for each sinusoidal wave was treated as a normally distributed random variable with a zero mean and a standard deviation of $\pi/3$. A sample of 500 base motions was generated.

Figure 3 shows that the response spectra of the generated time histories (Synt.) closely match the response spectra of the base motions achieved in LEAP-2015 and 2017 (exp.).

In the cases where spatial variability of void ratio was considered, a mean value of 0.606 was assumed for void ratio which corresponds to the target dry density of 1652 kg/m^3. A coefficient of variation (COV) of 7.8% was assumed based on the maximum range of variation reported by the testing facilities. Moreover, the correlation lengths of 0.5 and 5.0 meters were assumed in the vertical and horizontal directions, respectively. Finally, considering the fact that the sample was prepared in a controlled lab environment the average void ratio for each generated random field was limited to be within +/- 1% of the target mean void ratio (e.g., 0.606). Figure 4 shows a single realization of generated random field.

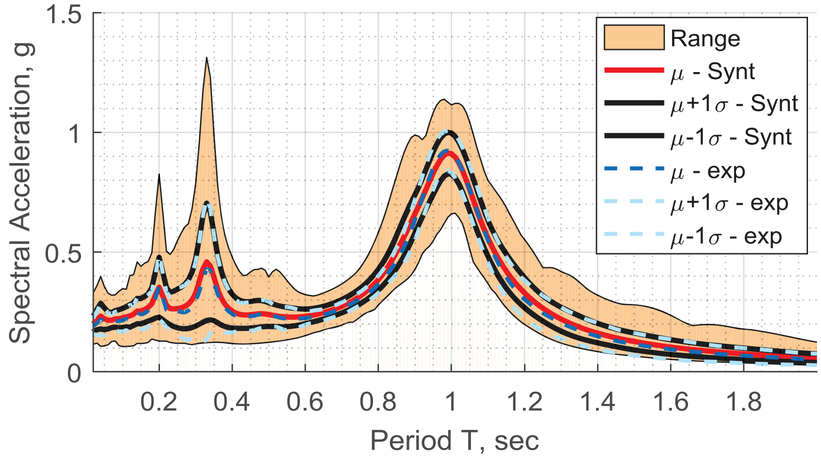

Figure 3: Spectral acceleration of the generated random base motions

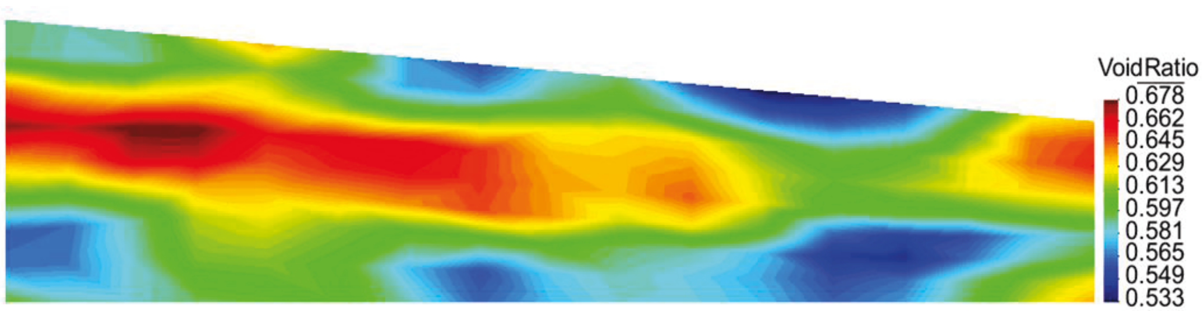

Figure 4. Distribution of initial void ratio of a single realization

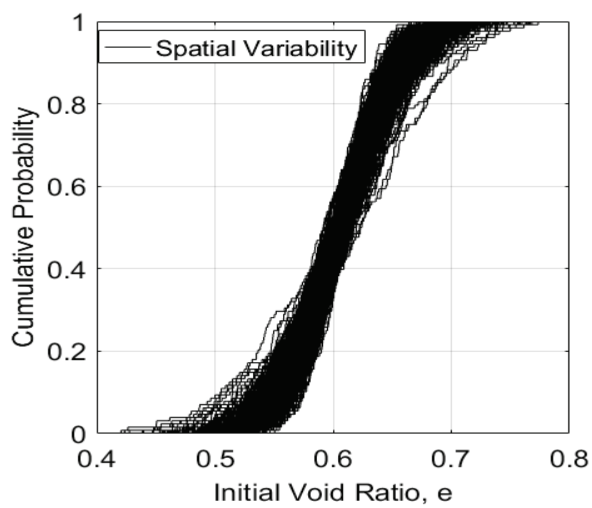

Figure 5. The cumulative probability distribution of all realizations of the spatial variability case

The cumulative distribution of all the 500 generated realizations is shown in Figure 5. The soil hydraulic conductivity was assumed to vary in accordance with the variability of void ratio following a relationship proposed in the previous work presented by the authors (ElGhoraiby et al., 2017).

RESULTS OF THE STOCHASTIC ANALYSIS

Results of two cases are reported here. The first case considers the base motion variability but the soil specimen is assumed to be homogeneous. The second case studies the base motion variability while accounting for spatial variability of void ratio in the specimen.

Figure 6 shows the excess pore pressure ratios at the locations of the pore pressure transducers P1 and P4 (Figure 1) for the homogeneous soil case. The results are presented in terms of the mean, the mean +/- one standard deviation of the results, and the range. Figure 7 shows the development of excess pore pressures for the spatial variability case at the same locations as those shown in Figure 6.

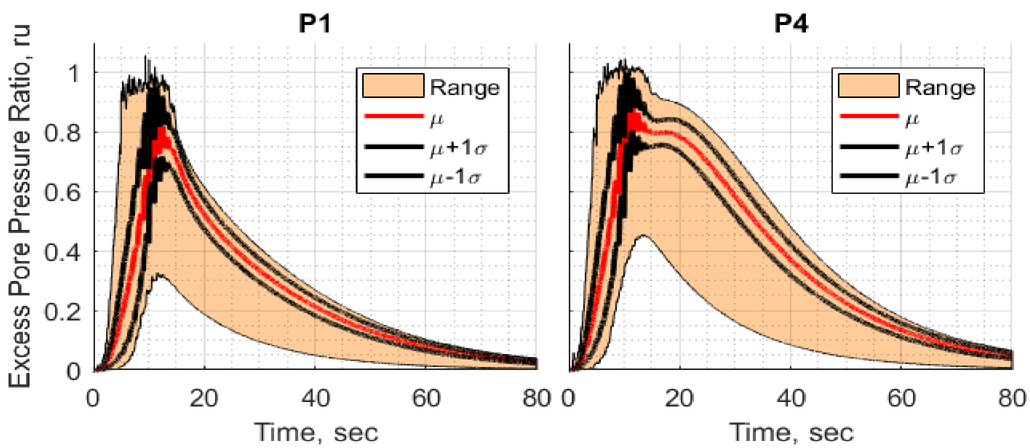

Figure 6: Excess pore pressure ratio for homogeneous case

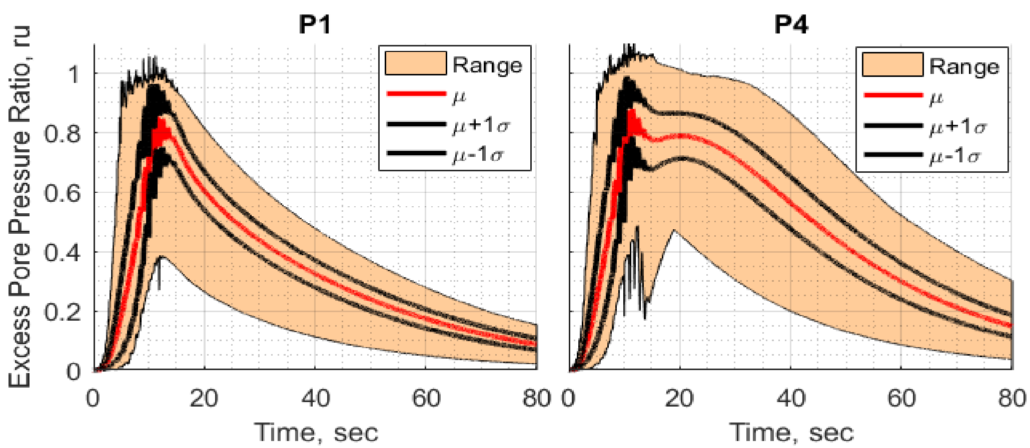

Figure 7: Excess pore pressure ratio for spatial variability case

Figure 8 shows the spread of lateral displacement time histories computed at point A located on the ground surface right above the central array of pore pressure transducers (Figure 1), as well as the time histories of the soil settlement computed at point B that is located on the ground surface right above the left array of pore pressure transducers. In this Figure the mean, mean +/-

one standard deviation and range of displacements for the homogenous case are presented. In a similar fashion, Figure 9 shows the lateral and vertical displacements for the spatial variability case.

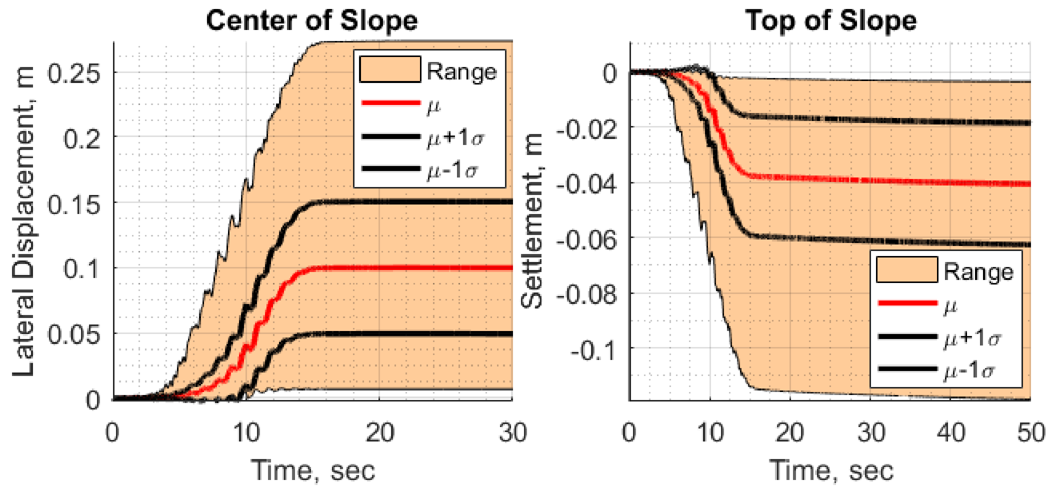

Figure 8: Time History of Displacement for Homogeneous Case

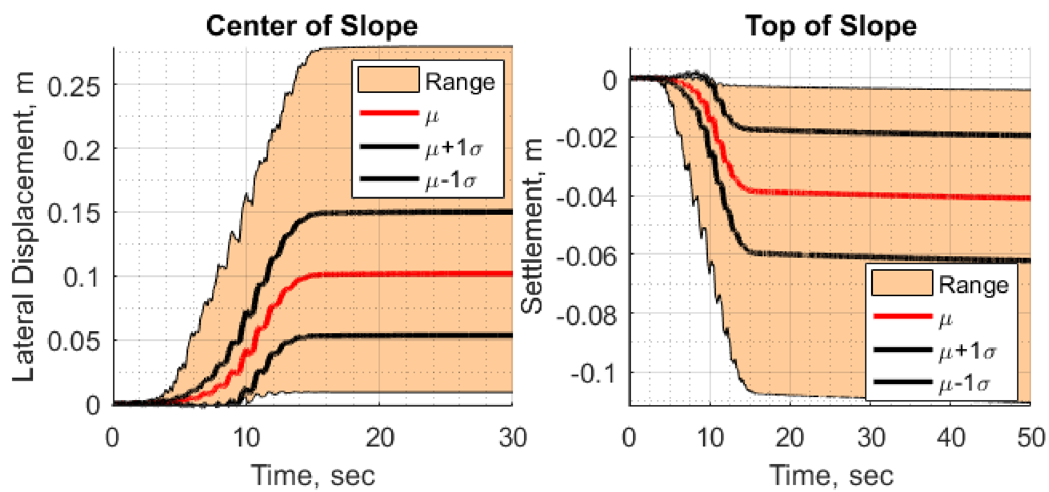

Figure 9: Time History of Displacement for Spatial Variability Case

Finally, the variations of the lateral displacement profile at the central portion of the soil specimen (where P1 to P4 sensors are located) for the homogeneous and spatially variable cases are shown in Figure 10.

DISCUSSION

The results obtained from the MC simulations provide the following observations. Firstly, a wide range of variation in the generated excess pore pressure is observed. The maximum excess pore pressure ratio ranged from 0.32 to 1.0 for the location of the pore pressure transducer P1 in the homogeneous case (Figure 6). For the location of P4 the range was from 0.45 to 1.0. A similar range can be seen in the spatial variability case (Figure 7). While the average rate of excess pore pressure generation is similar for the homogeneous and spatial variability cases, a slightly higher peak is observed in the spatial variability case. Additionally, the range of variation of the rate of excess pre pressure dissipation is wider in the spatial variability case.

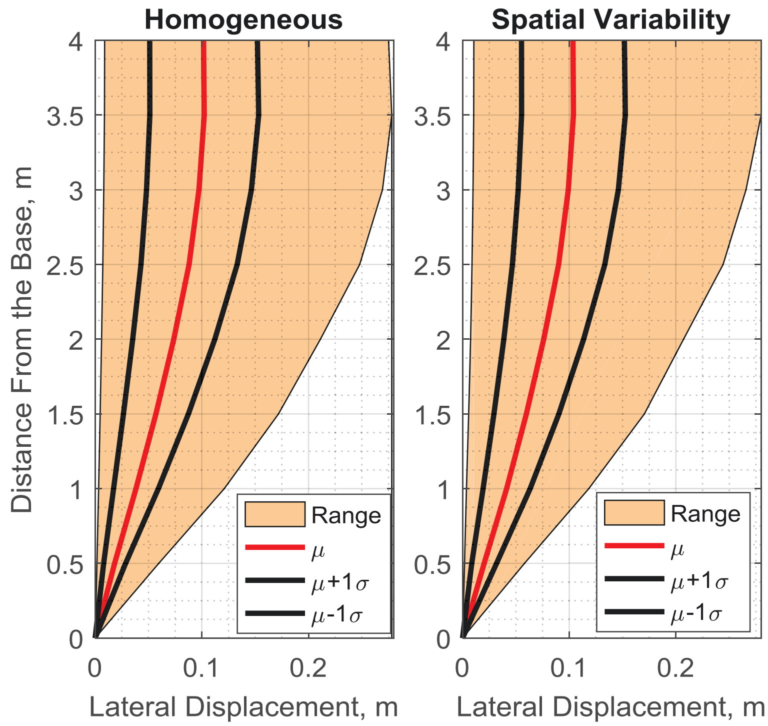

Figure 10: Soil profile lateral displacement at the center of the soil

Figure 11 shows the joint probability density of the peak ground acceleration and the maximum excess pore pressure ratio. These results correspond to the maximum excess pore water pressure at the location of pore pressure transducer P1 for the homogeneous MC simulations. It can be seen that the joint probability density reaches a peak at maximum excess pore pressure ratio of 0.94 and a peak ground acceleration (PGA) of 0.177g for the homogeneous case. The peak densities at two additional PGA magnitudes are also shown in the figure.

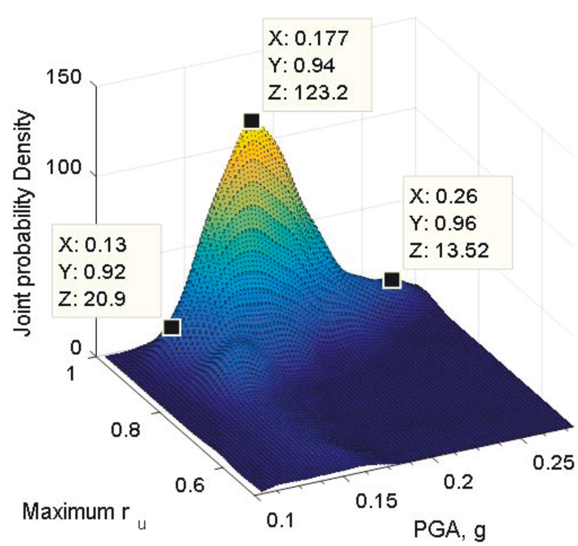

Figure 11: Joint probability density of PGA and max excess pore pressure

Figures 8 and 9 show the lateral displacement and settlement results at two different locations of the soil surface. In Figure 8, it can be seen that the soil has a mean of 10 and 4.05 cm for the lateral displacement and settlement of the homogenous case, respectively. While the coefficient of variation for the lateral displacement and settlement are 50.6 and 54.7%, respectively. For the spatial variability case the lateral displacement has a mean of 10.18 cm and coefficient of variation of 47.5% and the settlement has a mean of 4.07 cm and a coefficient of variation of 52.3%. While the differences are small, it can be seen that smaller deformations are observed for the spatial variability case in both the mean and range of variation. Ultimately, it appears that the soil response is more sensitive to the base motion variability than to the spatial variability under the assumed conditions. This agrees with the observations made by Lopez-Caballero and Modaressi-Farahmand-Razavi (2010). Similar observations can be obtained from the results shown in Figure 10 of the soil profile lateral displacement. A small difference between the mean response and coefficient of variation of the lateral displacements between the homogeneous and spatial variability cases is observed.

With such large range of variability in the soil displacement, it may be argued that the same level of uncertainty is present in the simplified methods used for lateral spreading estimation (Chu et al. 2006; Youd 1995; Youd et al. 2002). However, the types of uncertainty influencing the results of the two different analysis methods are quite different. The uncertainty present in the simplified method is an epistemic uncertainty that is based on the lack of information. On the other hand, the uncertainty studied here is the aleatory uncertainty that is based on the inherent variability of the soil.

CONCLUSION

The variability in the achieved base motion of LEAP-2015 and LEAP-2017 experiments was modeled as a random process and two cases of Monte Carlo simulations were performed to study the effects of this variability on the response of soil specimen in homogeneous and spatial variable conditions. It can be seen that a significant variation in the generated excess pore pressures and displacements is observed due to the variability in the base motion. A coefficient of variation of about 50% in the soil deformations emphasizes the high level of sensitivity of the response of the liquefiable soil to variations in the input motions. On the contrary a very small difference in the response is observed between the homogeneous case and spatial variability case. It should be noted that while the small difference between the two cases signifies a much lower sensitivity to the variation in the void ratio, this observation pertains only to the assumed conditions of the spatial variability where the average void ratio remained very close to the void ratio of the homogeneous soil. Therefore the sensitivity of the soil response to the variation in the soil density should be studied more closely under different assumptions.

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REFERENCES

Boulanger, R. W., and Montgomery, J. (2016). "Nonlinear deformation analyses of an embankment dam on a spatially variable liquefiable deposit." *Soil Dynamics and Earthquake Engineering*, Elsevier, 91, 222–233.

Chu, D. B., Stewart, J. P., Youd, T. L., and Chu, B. L. (2006). "Liquefaction-Induced Lateral Spreading in Near-Fault Regions during the 1999 Chi-Chi, Taiwan Earthquake." *Journal of Geotechnical and Geoenvironmental Engineering*, 132(12), 1549–1565.

Dafalias, Y. F., and Manzari, M. T. (2004). "Simple Plasticity Sand Model Accounting for Fabric Change Effects." *Journal of Engineering Mechanics*, 130(6), 622–634.

ElGhoraiby, M. A., and Manzari, M. T. (2017). "Small variability of soil density on response of liquefiable sloping ground." *International Journal of Terraspace and Engineering*, 9(1), 41–62.

ElGhoraiby, M. A., Manzari, M. T., and Hamdar, S. (2017). "Effects of Small Variability of Soil Density on the Consequences of Liquefaction." *Geo-Risk 2017*, American Society of Civil Engineers, Reston, VA, 11–20.

Gazetas, G., Debchaudhury, A., and Gasparini, D. (1981). "Random vibration analysis for the seismic response of earth dams." *Geotechnique*, (2), 261–277.

Griffiths, D. V, and Fenton, G. a. (1993). "Seepage beneath water retaining structures founded on spatially random soil." *Géotechnique*.

Kutter, B. L., Carey, T. J., Hashimoto, T., Zeghal, M., Abdoun, T., Kokkali, P., Madabhushi, G., Haigh, S. K., Burali d'Arezzo, F., Madabhushi, S., Hung, W.-Y., Lee, C.-J., Cheng, H.-C., Iai, S., Tobita, T., Ashino, T., Ren, J., Zhou, Y.-G., Chen, Y.-M., Sun, Z.-B., and Manzari, M. T. (2017). "LEAP-GWU-2015 experiment specifications, results, and comparisons." *Soil Dynamics and Earthquake Engineering*, 1–31.

Lopez-Caballero, F., and Modaressi-Farahmand-Razavi, A. (2010). "Assessment of variability and uncertainties effects on the seismic response of a liquefiable soil profile." *Soil Dynamics and Earthquake Engineering*, Elsevier, 30(7), 600–613.

Montgomery, J., and Boulanger, R. W. (2017). "Effects of Spatial Variability on Liquefaction-Induced Settlement and Lateral Spreading." *Journal of Geotechnical and Geoenvironmental Engineering*, 143(1), 4016086.

Popescu, R., Prevost, J. H., and Deodatis, G. (2005). "3D effects in seismic liquefaction of stochastically variable soil deposits." *Géotechnique*, 55(1), 21–31.

Rathje, E. M., Kottke, A. R., and Trent, W. L. (2010). "Influence of Input Motion and Site Property Variabilities on Seismic Site Response Analysis." *Journal of Geotechnical and Geoenvironmental Engineering*, 136(4), 607–619.

Sen, L. (2012). "Seismic Site Response Analysis Considering Ground Motion Variability and Site Property Variability." Hong Kong University of Science and Techonology.

Vasko, A. (2015). "An Investigation into the Behavior of Ottawa Sand through Monotonic and Cyclic Shear Tests." George Washington University.

Youd, T. L. (1995). "Liquefaction-Induced Lateral Ground Displacement." *3rd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*.

Youd, T. L., Hansen, C. M., and Bartlett, S. F. (2002). "Revised multilinear regression equations for prediction of lateral spread displacement." *Journal of Geotechnical and Geoenvironmental Engineering*, 128(12).