Spatial heterogeneity effects on K_0 loading

Kim, H. K.
School of Civil and Environmental Engineering, Kookmin University, Korea

Santamarina, J. C.
School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, U.S.A

Keywords: spatial variability, stiffness, random variable, particulate mixture

ABSTRACT: Spatial heterogeneity prevails in soils, even in remolded specimens formed in the laboratory under carefully controlled conditions. Spatial variability prompts the emergence of mechanical phenomena that are not encountered in homogeneous media. The purpose of this study is to explore phenomena associated to spatial variability in soils, taking into consideration their particulate nature. We focus on the effect of variability in soil stiffness on the load-deformation response under zero-lateral strain conditions, using complementary finite element simulations (correlated random media) and experiments (rubber-sand mixtures). Results show the development of non-homogeneous stress and strain fields, intricate load transfer and stress concentration along percolating stiff zones, the reduction in K_0 values, more complex interpretation of wave propagation traces for the characterization of small strain stiffness, and suggest judicious use of mixture formulas.

1. INTRODUCTION

Spatial heterogeneity is an inherent characteristic in natural soils. The spatial variability of geotechnical engineering properties can be captured using statistical data such as the mean trend μ, the coefficient of variation COV, and spatial correlation (Vanmarke 1977; DeGroot and Baecher 1993; Lacasse and Nadim 1996; Phoon and Kulhawy 1999).

The role of spatial variability in geotechnical engineering problems has been reported in many aspects of soil behavior including: deformation (Baecher and Ingra 1981; Zeitoun and Baker 1992; Paice et al. 1996), strength (Popescu et al. 1996; Griffiths and Fenton 2001), conductivity (Renard and de Marsily 1997; Wen and Gómez-Hernández 1996), and diffusion (Schiffman and Gibson 1964; Nishimura et al. 2002).

Phenomena not observed in homogeneous media may "emerge" in heterogeneous soils. These are investigated in this study, where soils are subjected to K_0 loading. Numerical and experimental methods are used (the complete data set can be found in Kim 2005).

2. NUMERICAL SIMULATION

The local and global mechanical response of heterogeneous soils subjected to K_0 loading is explored first using finite element simulations.

2.1 Procedure

The horizontally constrained square medium is discretized into 100x100 four-node plane strain elements, and the soil is modeled using the modified Duncan-Chang material model (Code: ABAQUS 2007).

The small-strain shear modulus at 1kPa confining stress, α, is selected as a uniformly distributed random variable. Spatially heterogeneous specimens are realized as correlated random fields using the matrix decomposition technique (details in El-Kadi and Williams, 2000). Each realization is a statistically defined non-uniform medium with a prescribed mean, standard deviation and correlation length.

2.2 Stress-induced homogenization

Media realized with the same coefficient of variation in initial elastic modulus (COV[α]=0.3) and two different correlation lengths (L/D~0 and 0.2) are subjected to K_0 loading. Cumulative volume fractions for the normalized mean principal stress when the vertical load is 25kPa and 500kPa are shown in Fig.1. The stress distribution becomes homogenized and the local stiffness heterogeneity decreases as the applied load increases. Note that a narrower stress distribution is observed in media with correlation length L/D=0.2, which suggests a more pronounced tendency to arching in uncorrelated media.

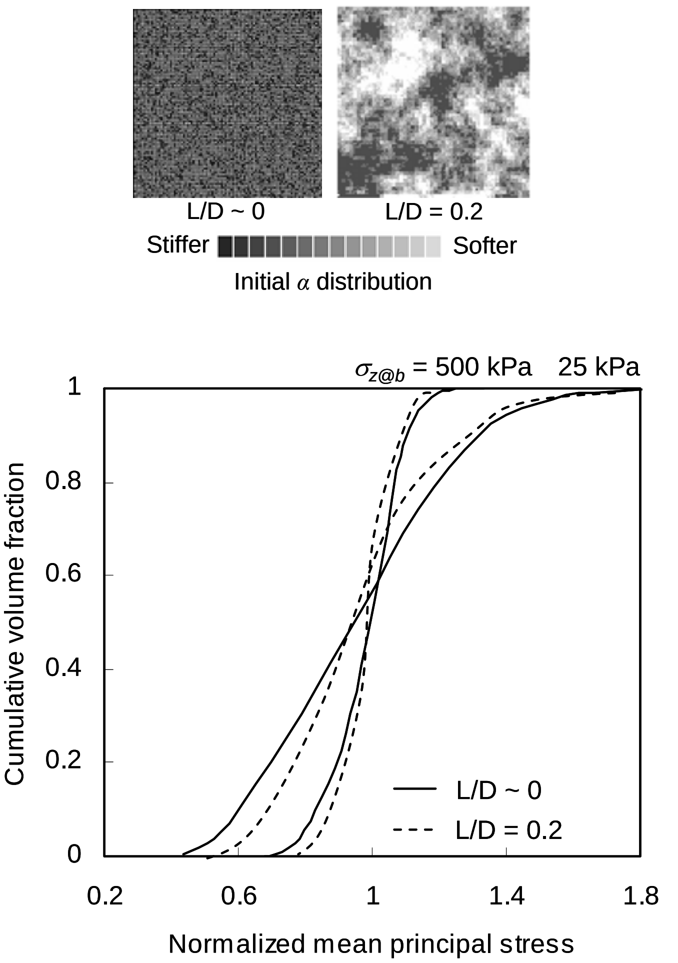


Fig. 1 Stress-induced homogenization

2.3 Increased compressibility

Correlated heterogeneous media are realized with the same correlation length *L/D*=0.2 and mean initial stiffness μ[*α*], but different variance COV[*α*]=0.0 (homogeneous), 0.1, 0.3, and 0.5. Fig. 2 shows the K_0 load-deformation response in each case. Higher compressibility is observed for higher variance in stiffness distribution, in agreement with the earlier studies with linear elastic material models (Baecher and Ingra, 1981; Zeitoun and Baker, 1992; Paice et al., 1996).

2.4 Stress focusing

The internal vertical stress distribution for the cases reported above are presented in Fig 3 (L/D=0.2, same μ[α], COV[α]=0.1, 0.3, and 0.5 – Note: the stress distribution is homogenous in COV[α]=0.0). Media with higher heterogeneity show clear contrast in internal vertical stress distribution.

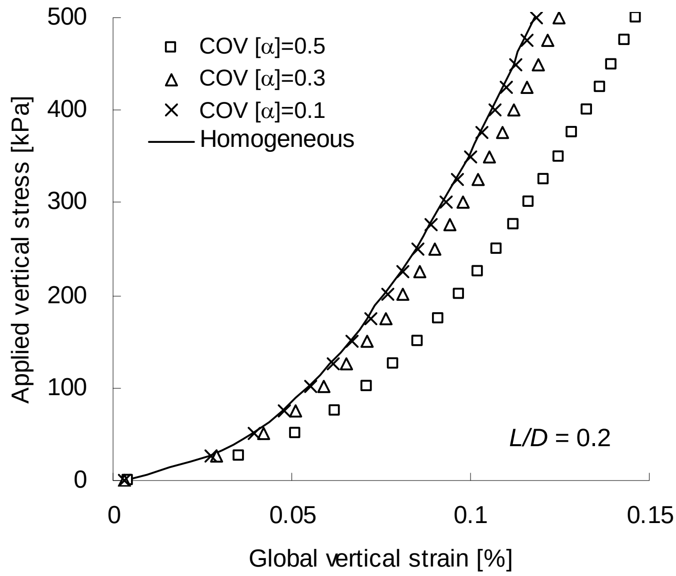


Fig. 2 Increased compressibility with higher variance

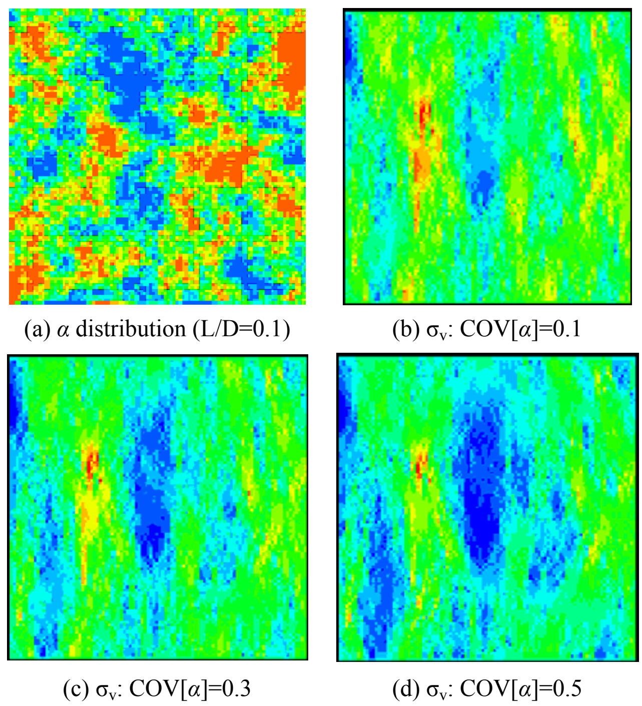


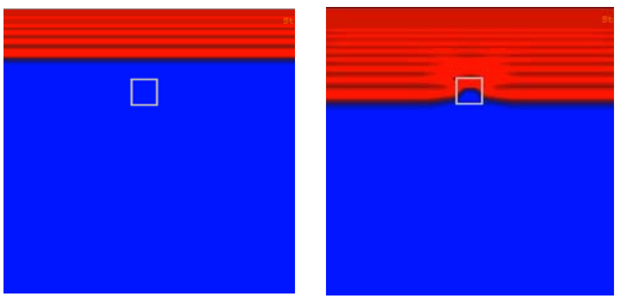
Fig. 3 Vertical stress focusing: Variance leads to arching and load transfer through stiffer vertical columns

2.5 Reduction in K_0

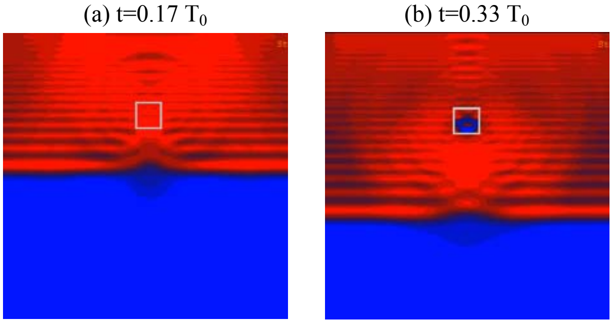
The value of K_0 for the simulations shown above are K_0=0.51 for COV[*α*]=0.1, $K_0=0.50\sigma_v'$ for COV[*α*]=0.3, and $K_0=0.48\sigma_v'$ for COV[*α*]=0.5. Therefore, spatial variability in soils leads to arching, vertical load transfer along stiffer columns, and the decrease in horizontal load transfer.

2.6 Altered wave propagation
Mode conversion and diffraction healing

The small-strain characterization of soil mass using wave propagation is particularly affected by heterogeneity. Consider a plane shear-wave propagating through a medium with a square inclusion 10 times softer than the background (Fig. 4). Mode conversion at the interface between the host medium and the inclusion causes the development of a P-wave that travels ahead of the diffracted S-wave (Fig. 4c). On the other hand, diffraction healing "hides" the anomaly which becomes undetectable at a distance of 4 to 6 times the inclusion size beyond the inclusion. Together, the development of a head P-wave and diffraction healing affects the interpretation of wave-propagation data and the characterization of heterogeneous media (other consequences of heterogeneity in wave propagation are explored in Kim 2005).



(a) $t=0.17\ T_0$ (b) $t=0.33\ T_0$



(c) $t=0.50\ T_0$ (d) $t=0.67\ T_0$

Fig. 4 Plane S-wave propagation in a medium with a low velocity inclusion. Notation: $T_0 = L/V_{s0}$, the inclusion size $D \approx 1.6\lambda$, t= time.

3. EXPERIMENTAL STUDY

The behavior of a soil mass with large soft inclusions is experimentally studied next using a mixture of sand and large rubber chips (much larger than the sand grains). Material properties follow:

- Ottawa 50/70 sand: $D_{50} = 0.35$mm, $G_s = 2.65$, E ~ 5.9×10^7 kPa
- rubber chips: $D_{50} = 3.5$mm, $G_s = 1.14$, E ~ 1020kPa

3.1 *Zero-lateral strain compressibility*

The K_0 load-deformation response is determined in a modified oedometer cell that includes bender elements on the top cap and bottom plate to measure a small strain elastic wave velocity.

Fig. 5 shows the evolution of the constrained modulus computed between two successive loading stages during loading for mixtures. The global stiffness decreases with increasing volume fraction of soft inclusions V_{rubber}.

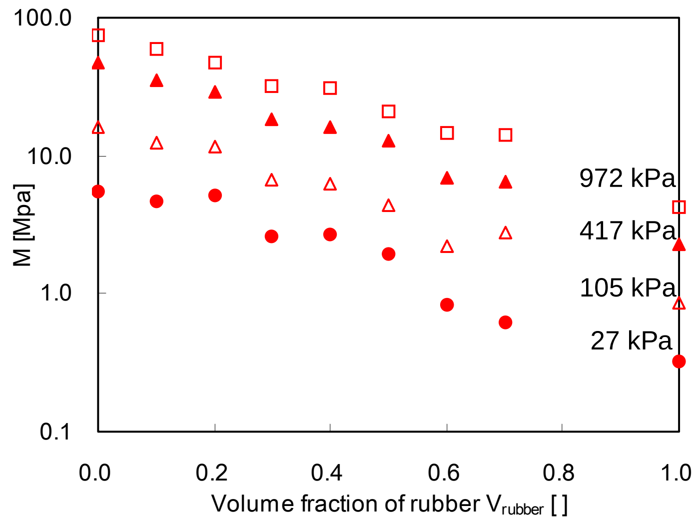


Fig. 5 Constrained modulus in sand-rubber mixtures versus applied vertical stress.

3.2 *Elastic wave propagation*

The measured S-wave velocity is plotted in Fig. 6 in terms of V_{rubber}. In contrast to the constrained modulus, the maximum shear wave velocity is observed in the $V_{rubber} = 0.2$ mixture, and the shear wave velocity decreases significantly when the rubber volume fraction exceeds V_{rubber}>40%. Stress focusing (shown in Fig 3) and wave propagation phenomena (Fig 4) explain this result: higher stress in the sand leads to higher local wave propagation velocity.

3.3 *K_0 coefficient measurement*

The oedometer is instrumented with strain gauges installed in the horizontal direction of the cell wall to determine the radial stress in the soil-rubber mixture. K_0 values are plotted in Fig. 7. While variability is high, results suggest lower K_0 values in mixtures V_{rubber}= 0.2~0.4, in agreement with numerical results (Section 2.5).

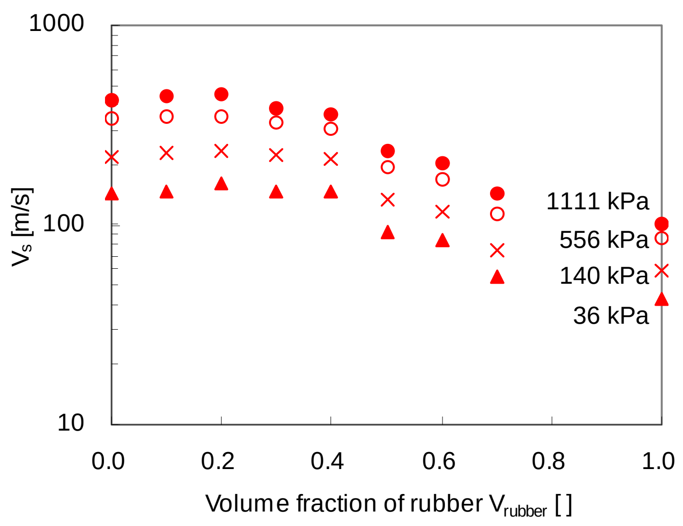


Fig. 6 Shear wave velocity in sand-rubber mixtures

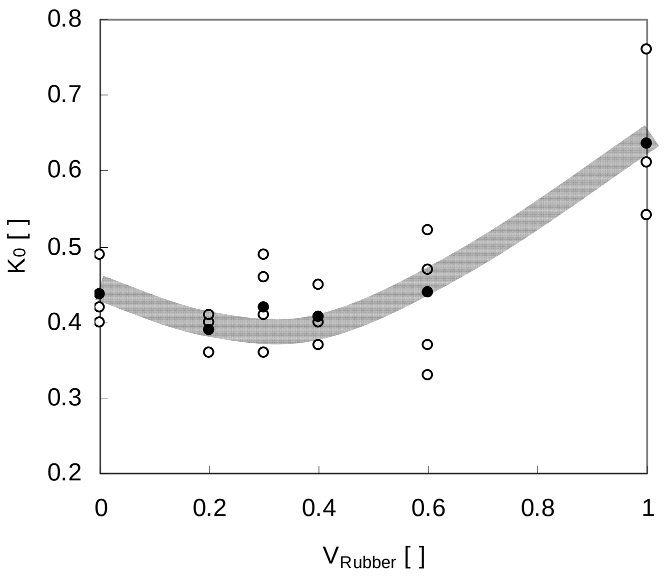


Fig. 7 K_0 values in the soil-rubber mixtures (black dots are the average values)

4. CONCLUSIONS

Internal stiffness heterogeneity in particulate materials promotes intricate local mechanisms and the emergence of new global behavior in zero-lateral strain loading, including stress induced homogenization, stress focusing, and reduction in K_0 coefficient. The macroscale characterization with wave propagation techniques must take into consideration the coupling between quasi-static effects and wave propagation effects, including mode conversion and diffraction healing.

ACKNOWLEDGEMENTS

This research was supported by a grant on Scale Effects in Soils from the National Science Foundation, and by the Goizueta Foundation.

REFERENCES

Beacher, G.B. and Ingra, T.S. (1981). “Stochastic FEM in settlement predictions,” J. Soil Mech. Fdns. Div., ASCE, 107(4), 449-463

DeGroot, D.J. and Baecher, G.B. (1993). “Estimating autocovariance of in-situ soil properties,” J. Geotech. Engng., ASCE, 119(1), 147-166

Duncan, J.M. and Chang, C.Y. (1970). “Nonlinear analysis of stress and strain in soils,” J. Soil Mech. Fdns. Div., ASCE, 96(5), 1629-1653

El-Kadi, A.I. and Williams, S.A. (2000). “Generating two-dimensional fields of auto-correlated, normally distributed parameters by the matrix decomposition technique,” Ground Water, 38(4), 530-532

Griffiths, D.V. and Fenton, G.A. (2001). “Bearing capacity of spatially random soil: the undrained clay Prandtl problem revisited,” Géotechnique, 51(4), 351-359

Kim, H.-K. (2005). Spatial variability in soils: stiffness and strength, Ph.D. thesis, Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, U.S.A.

Lacasse, S. and Nadim, F. (1996). “Uncertainties in characterizing soil properties,” Proc., Uncertainty in the Geologic Environment: from Theory to Practice, Shackelford, C.D., Nelson, P.P., and Roth, M.J.S., eds., ASCE, Madison, WI, 49-75

Nishimura. S.I., Shimada, K., and Fujii, H. (2002). “Consolidation inverse analysis considering spatial variability and non-linearity of soil parameters,” Soils and Foundation, 42(3), 45-61

Paice, G.M., Griffiths, D.V. and Fenton G.A. (1996). “Finite element modeling of settlements on spatially random soil,” J. Geotech. Geoenv. Engng., ASCE, 122(9), 777-779

Phoon, K.K. and Kulhawy, F.H. (1999). “Characterization of geotechnical variability,” Can. Geotech. J., 36, 612-624

Popescu, R., Prevost, J.H. and Deodatis, G. (1996). “Influence of spatial variability of soil properties on seismically induced soil liquefaction,” Proc., Uncertainty in the Geologic Environment: from Theory to Practice, Shackelford, C.D., Nelson, P.P., and Roth, M.J.S., eds., ASCE, Madison, WI, 1098-1112

Renard, Ph. and de Marsily, G. (1997). “Calculating equivalent permeability: a review,” Adv. Water Resour., 20, 253-278

Santamarina, J.C., Klein, K.A., and Fam, M.A. (2001). Soils and waves, John Wiley and Sons Ltd. New York

Schiffman, R.L. and Gibson, R.E. (1964). “Consolidation of non-homogeneous clay layers,” J. Soil Mech. Fdns. Div., ASCE, 4043, 1-30

Vanmarcke, E.H. (1977). “Probabilistic modeling of soil profiles,” J. Soil Mech. Fdns. Div., ASCE, 103(11), 1227-1246

Wen, X. and Gómez-Hernández, J.J. (1996). “Upscaling hydraulic conductivities in heterogeneous media: an overview,” J. Hydrol., 183, ix-xxxii

Zeitoun, D.G. and Baker. R. (1992). “A stochastic approach for settlement predictions of shallow foundations,” Géotechnique, 42(4), 617-629