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Modeling added spatial variability due to soil improvement: Coupling FEM with binary random fields for seismic risk analysis

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ABSTRACT

A binary mixture homogenization model is proposed for predicting the effects on liquefaction-induced settlement after soil improvement based on the consideration of the added spatial variability between the natural and the treated soil. A 2D finite element model of an inelastic structure founded on a shallow foundation was coupled with a binary random field. Nonlinear soil behavior is used and the model is tested for different mesh size, model parameters and input motions.

Historical evidence as well as physical and numerical modeling indicate that improved sites present less liquefaction and ground deformation. In most cases this improvement is modeled as homogeneous; however, in-situ measurements evidence the high level of heterogeneity in the deposit. Inherent spatial variability in the soil and the application of some soil improvement techniques such as biogrouting and Bentonite permeations will necessary introduce heterogeneity in the soil deposit shown as clusters of the treated material in the natural soil. Hence, in this study, improvement zones are regarded as a two-phase mixture that will present a nonlinear relation due to the level of complexity of seismic liquefaction and the consequent settlement in a structure. This relation is greatly affected by the mechanical behavior of the soils used and the input motion. The effect on the latter can be efficiently related to the equivalent wave period as the proposed homogenization model depends on the stiffness demand of the input motion.

1. Introduction

Soil improvement techniques such as biogrouting and Bentonite permeations are becoming widely used to strengthen soils and mitigate liquefaction. Significant advances have been made in the equipment and methods used although, the high degree of spatial variability introduced in the design and its effect of the system's performance are less known [1]. The success of these techniques is related to two factors: (1) the effectiveness of the method related to how much of the soil is being changed – and (2) the efficiency in improving the soil behavior related to how much are the consequences optimized. The effectiveness can be measured by the spatial fraction of the treated soil with respect to the total treatment area, for example the amount of gravel, clay or bacteria introduced in a sand deposit. However, the efficiency is related to the different spatial configurations on the vertical as well as in the horizontal direction which will present an important uncertainty in the response. A success function relating effectiveness and the average efficiency could be defined in order to optimize the soil improvement consequences.

For obtaining an average behavior of the improved ground, a homogenization method has to be defined. In this paper, to analyze the effects of added spatial variability due to soil improvement techniques, binary random fields are coupled to a 2D finite element model (FEM) with soil-structure interaction. The former is used to generate the treated ground soil as a two-phase mixture composed of the reference soil and the added improved material. The latter is a two-story inelastic structure with a shallow foundation on loose-to-medium sand (LMS). In the treatment zone, a medium-to-dense sand (MDS) is added. Montoya-Noguera and Lopez-Caballero [2] analyzed the effect of the different spatial distributions on the interactions between the two materials as it

Abbreviation: D_{5-95}, Predominant duration; EQ, Earthquake; FEM, Finite element model; FF, Free-field; f_{str}, Fundamental frequency; GEM, Generalized Effective Medium; IM, Intensity measures; I_A, Arias intensity; LMS, Loose-to-medium sand; MDS, Medium-to-dense sand; PHA, Peak horizontal acceleration; PHV, Peak horizontal velocity; p_w, Fluid pore pressure; $|u_z|$, Relative surface settlement of the structure with respect to FF; SSI, Soil-structure interaction; TF, Transfer function; $T_{V/A}$, Period of equivalent harmonic wave; V_s, Shear wave velocity; $V_{s\,30}$, Geometric mean of V_s for the upper 30 m; β_1, β_2, Horizontal and vertical auto-regressive coefficients; Δp_w, Excess pore pressure; $\Delta|u_z|$, Relative difference of $|u_z|$; γ, Spatial fraction; γ_c, Critical spatial fraction; κ, Hydraulic conductivity (or permeability); ξ, Damping

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changes the pore-pressure migration and average liquefaction in the model. The present study extends the work in three main directions:

1. The relation between the technique effectiveness and the average efficiency, defined as the success function, is evaluated for different input motions. To measure the efficiency, the relative surface settlement of the structure with respect to free-field ($|u_z|$) at the end of shaking is used.
2. Investigating the sensitivity of the analysis regarding the mesh size discretization and the material's behavior.
3. The success function is related to different homogenization theories. First traditional theories regarding only the geometry of the mixture are tested and finally an advanced method is proposed.

1.1. Soil improvement and soil mixtures

There are not many real-size experimental observations for reduction of liquefaction potential with spatial measures showing the distribution of treated zones. Even if in reality, grouted columns are designed to have specific diameters and spacings, the material is in most cases an heterogeneous mixture of the added soil (or material) and the original one. Generally, it is difficult to measure the mechanical properties of these columns in the field. Lambert et al. [3] performed laboratory tests in samples from soil-cement mixed columns and found heterogeneities in the sides as well as in the core of the columns, that consequently affected the mechanical properties. Different studies have assessed the fraction of soil remaining in the columns, for example Boulanger et al. [4] estimated it at about 20%.

DeJong et al. [5,6] presented results of large-scale and centrifuge tests of bio-grouting. Resistivity in-situ measurements were evaluated before and after bio-grouting. Before improvement, soil variability appears to be continuous and the horizontal correlation is considerately higher than the vertical correlation. After treatment, some areas present more bacteria-induced cementation and a clear distinction is shown between clusters or pockets. Centrifuge tests presented by DeJong et al. [5] also show the clusters of modified soil in a discrete distribution. This distribution might be caused by clogging of the soil pore spaces and more calcite near the injection point [7].

Evidence of the decrease of liquefaction resistance of the mixture compared to that of uniform samples is found in undrained cyclic triaxial tests on sand-gravel [8] and sand-silt [9] mixtures and centrifuge tests on mixtures of sand with different densities [10,11] and with different permeabilities [12]. In general, it was found that the effect of the loose sand zone was to induce increased excess pore water pressure (Δp_w) in the surrounding dense sand or create drainage paths, through which the Δp_w can be drained out causing differential settlements. Most of these studies have dealt with the liquefaction triggering and have not evaluated the response of structures underlying liquefiable soil deposits or the liquefaction-induced settlements.

1.2. Homogenization theories

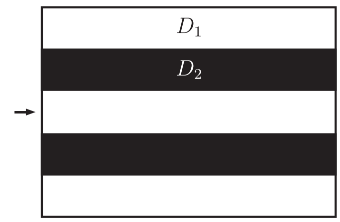
The process of homogenization consists of deriving the effective properties for an heterogeneous system so that it can be viewed as homogeneous on a particular macroscopic scale depending on the property of interest [13]. The effective medium depends on the *geometry* (e.g. shape and size of particles) and the *topology* or connectivity among particles. A brief description of the homogenization theories used in this study is presented below:

1.2.1. Traditional theories

Traditional homogenization theories are often used to describe geotechnical properties. For example, the work on spatial variability effect on bearing capacity of Popescu et al. [14] often compares the average results of the heterogeneous soil models with the "corresponding homogeneous soil". According to the authors, the homogenization is the mean value of the Monte Carlo simulations; although this is only true for vertically layered materials (i.e. parallel to the bearing capacity) described by classical homogenization theories. If, on the contrary, the layers are horizontal (i.e perpendicular or serial) the effective properties of the homogeneous model would be a harmonic average. It is clear that for random fields, these are only extreme cases which are known as Wiener [15] bounds. For a mixture of properties D_1 and D_2 where is the spatial fraction of D_2, the Wiener [15] bounds are defined as:

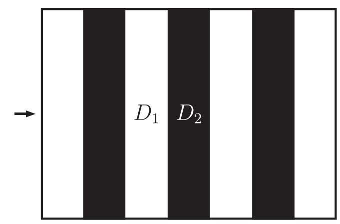
- Parallel:

$$D_{\|} = (1-\gamma)\cdot D_1 + \gamma\cdot D_2$$



- Serial:

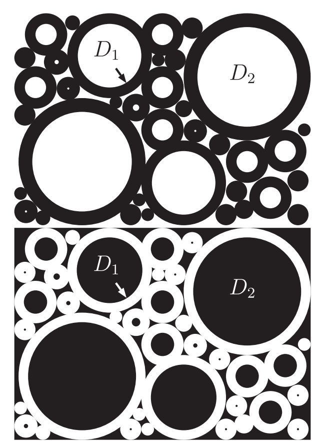
$$D_{\perp} = \frac{1}{\frac{(1-\gamma)}{D_1} + \frac{\gamma}{D_2}}$$



Another case that can be exactly modeled as homogeneous consists of concentric-shell structures, i.e. one material coating the other in spheres of different size. When $D_2 > D_1$, the properties can be described by the HS equation expressed by Hashin and Shtrikman [16] as:

- Material 1 coating material 2:

$$D_{HS^+} = D_2 + \frac{1-\gamma}{\frac{1}{D_1 - D_2} + \frac{\gamma}{d\cdot D_2}}$$



- Material 2 coating material 1:

$$D_{HS^-} = D_1 + \frac{\gamma}{\frac{1}{D_2 - D_1} + \frac{1-\gamma}{d\cdot D_1}} \quad (4)$$

where d is the dimensionality. This parameter binds the model to fluctuate between the Wiener bounds; hence, when d is equal to unity, they become the parallel bound and as it tends to infinity it approaches the perpendicular one. Actually, HS bounds are narrower than the Wiener bounds and are often used as they are simple and intuitive. However, they still give wide predictions, specially if the ratio between the material properties is big.

1.2.2. Generalized effective medium (GEM)

Traditional homogenization theories are based on the geometric arrangements among the phases, e.g. parallel and series [15] or