Three-Dimensional Numerical Simulations of Granular Column Improved Layered Liquefiable Soil Deposit

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Abstract. This paper presents numerical analysis on the mitigation effect of granular columns for layered liquefiable soil deposit. 3D simulations of the centrifuge shaking table tests conducted at the University of Colorado Boulder's 400 g-ton centrifuge facility are using a plasticity constitutive model for large post-liquefaction deformation of sand (CycLiq), via the FLAC^{3D} finite difference code. The simulations investigate the response of a layered liquefiable soil deposit improved by granular columns, under horizontal Kobe earthquake motion input. The results suggest that the constitutive model and FLAC^{3D} simulation method can be used to successfully capture the seismic response of granular columns improved liquefiable ground. Granular columns can significantly enhance drainage, which suppresses the build-up of excess pore pressure and increases the rate of excess pore pressure dissipation. Meanwhile, it also reinforces the ground by reducing the horizontal and vertical displacements.

Keywords: Granular columns · Soil liquefaction · Centrifuge tests simulation · FLAC^{3D}

1 Introduction

Soil liquefaction induced by earthquakes has caused many cases of foundation failure, leading to damage of geotechnical structures such as slopes, embankments and bridges. The installation of improvement measures offer an effective procedure for stabilizing an otherwise potentially liquefiable sand deposit. Hausler and Sitar [1] compiled over 90 case histories on the performance of improved sites from 14 earthquakes in Japan, China, Turkey, and the United States, of which the methods include from conventional densification methods like sand compaction piles to less common lateral restraint-based methods such as sheet pile walls or deep soil mixing grids. Seed and Booker [2] proposed the construction of granular columns as a mitigation strategy to ensure the stabilization of a medium dense sand layer.

Beyond the observations of case histories, several centrifuge tests have been conducted to investigate the mitigation mechanism of granular column for liquefiable soil deposit. Brennan et al. [3] carried out a series of centrifuge tests on level sand beds treated

with a group of piles without surface structures, to investigate the effect of drainage. Adalier et al. [4] focused on the overall site stiffening effects rather than the drainage effects. Badanagki et al. [5] investigated how granular columns enhance drainage and shear reinforcement in both level and gentle slopes to achieve liquefaction mitigation and restrict lateral spreading. These results of centrifuge tests have provided excellent basis validation of numerical simulations for further study.

Li et al. [6] performed a two-dimensions simulation of the centrifuge tests conducted by Badanagki et al. [5], in OpenSees, using PDMY02 and SANISAND soil constitutive models. Dinesh et al. [7] simulated sites with various granular column area replacement ratio using PM4Sand constitutive model in FLAC program in plane strain.

This study performs 3D simulation of the centrifuge tests conducted by Badanagki et al. [5], using a plasticity constitutive model for large post-liquefaction deformation of sand (CycLiq) [8], via the FLAC^{3D} finite difference code [9]. The applicability of the constitutive model and the numerical platform for such simulations are assessed via comparisons between numerical and experimental results.

2   Modeling of a Gentle Slope Improved with Granular Columns

2.1   Model Description

The centrifuge test simulated in this study was conducted at the University of Colorado Boulder's (CU) 400 g-ton (5.5 m-radius) centrifuge facility to investigate the influence of granular column improvement on a gently sloping layered liquefiable soil deposit [5], as shown in Fig. 1. A grid of 1.75 m-diameter granular columns were installed in the left half of the ground, separated by 3.5 m (center-to-center) with an area replacement ratio of 20%, which will be taken as Model 1. The other half, taken as Model 2, was left untreated as a benchmark. The properties of sand, silt, and gravel are shown in Table 1.

The numerical simulation of the centrifuge test is performed using the Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC^{3D}). The nonlinear, elasto-plastic response of soil and columns was modeled with a plasticity constitutive model for large post-liquefaction deformation of sand proposed by Wang et al. [8–11], referred to as CycLiq [8]. Zou et al. [9] implemented the model in FLAC^{3D}, and validated it by simulating undrained cyclic torsional shear tests, triaxial compression tests, cyclic triaxial tests and centrifuge tests.

Figure 1 presents the schematic of the slopes, of which the length, width and height are 66.9 m, 26.3 m and 18 m. The thickness of the loose Ottawa sand is 8 m while that for the top two layers is 2 m [7]. The circular cross section of the column is modified to a 1.55 m-side length square with identical area for simplicity. As shown in Table 2, the model parameters of Ottawa sand were calibrated previously by He et al. [12] and Zou et al. [9], only minor modification was made in this study with respect to the dilatancy parameter $d_{re,1}$. The simulation of a typical clic torsional shear test by Vargas et al. [13] using this set of parameters in FLAC^{3D} is shown in Fig. 2, good agreement is achieved between test and simulation. Relevant element test results of the Monterey Sand and Silt used in the centrifuge test are not available, the model parameters are estimated using those of Toyoura sand, as reported by Zou et al. [9].

Table 1. Properties of sand, silt, and gravel.

Soil (Dr%)	Gs	emax	emin	Permeability (cm/s)
Monterey sand (90%)	2.64	0.84	0.54	0.0529
Silt	2.65	1.35	2.65	0.00003
Loose Ottawa sand (40%)	2.65	0.81	0.53	0.0141
Dense Ottawa sand (90%)	2.65	0.81	0.53	0.0119
Granular columns	1.732	0.92	0.62	2.9
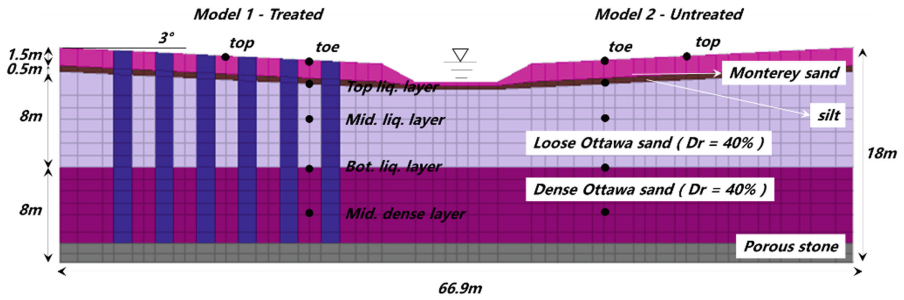
Fig. 1. A cross-sectional view of the model sloping ground treated with granular columns.

Table 2. Model parameters of Ottawa sand and gravel

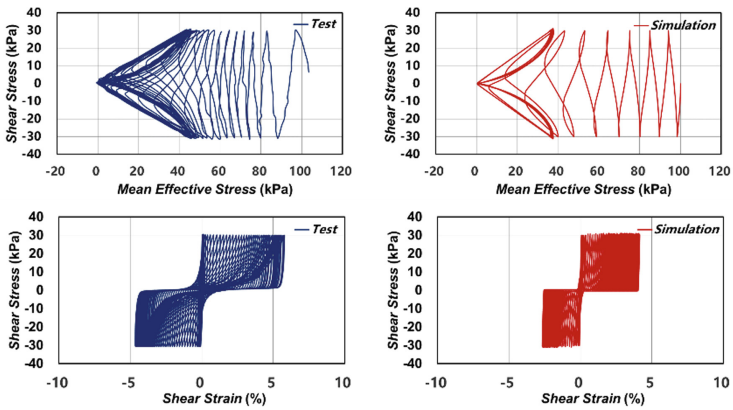|	G_0	κ	h	$d_{re,1}$	$d_{re,2}$	d_{ir}	α	$\gamma_{d,r}$	n^p	n^d	M	λ_c	e_0	ξ
Ottawa sand	210	0.01	1.5	1.4	40	3.0	30	0.05	2.2	6.0	1.17	0.0112	0.78	0.715
Gravel	360	0.018	0.56	0.55	38	0.95	5.0	0.20	0.5	18.0	1.54	0.018	0.715	0.70

Fig. 2. Calibration of the cyclic torsional shear test with modified model parameters of Ottawa sand

2.2 Simulation Process

The simulation starts with the calculation of the initial stress field by elastoplastic calculation and seepage calculation. Subsequently, the earthquake motion is input during dynamic analysis with fluid-mechanical interaction. The mechanical and fluid boundary conditions are: 1) The base is fixed in the Z-axis direction, while the accelerations are input in the X-axis direction. 2) Considering the flexible-shear-beam (FSB) container was used to model free-field conditions, the nodes with the same height located at the left and right sides of the numerical model are tied, in the direction of the earthquake input. 3) The front and the back of the model are both fixed in the Y-axis direction. 4) All sides except the top surface are undrained, while the pore pressure of the top is 0 kPa.

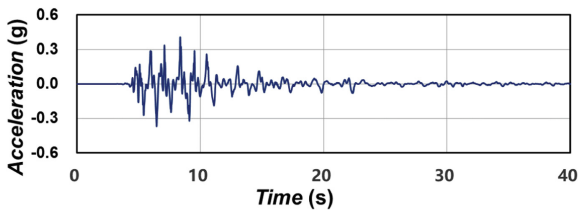The input motion at the base is shown in Fig. 3.

Fig. 3. The modified Kobe earthquake input motion.

3 Results and Discussion

3.1 Influence of Drainage in Granular Columns on Excess Pore Pressure Ratio

Figure 4 compares the computed excess pore pressure ratio (r_u) time histories at various depths in both treated and untreated sides for the test and numerical simulation. The test results show that liquefaction (defined asr_u) happened in both sides within the loose layer of Ottawa sand. Compared with the untreated side, the drainage of granular columns resulted in a notable speedup in the dissipation rate of excess pore pressure.

The numerical simulation results show good overall agreement with the recorded time histories of excess pore pressure ratio both during and after the shaking in most of the measurement points. At greater depths in the untreated side, the model slightly underestimates the rate of excess pore pressure dissipation, contributing to greater excess pore pressure ratio after shaking. This may be due to the constant soil permeability adopted in the numerical simulation. Soil permeability has been suggested to increase as excess pore pressure increases [6], which means the hydraulic conductivity (k) tends to increase during shaking. The simulation and test results at the two most shallow points in the treated side show some differences. However, the test results at these two locations does seem somewhat odd.

Figure 5 shows the numerical results of excess pore pressure contour immediately after shaking. Comparison between the two halves of the model clearly show that the granular columns can significantly reduce the excess pore pressure within the liquefiable ground.
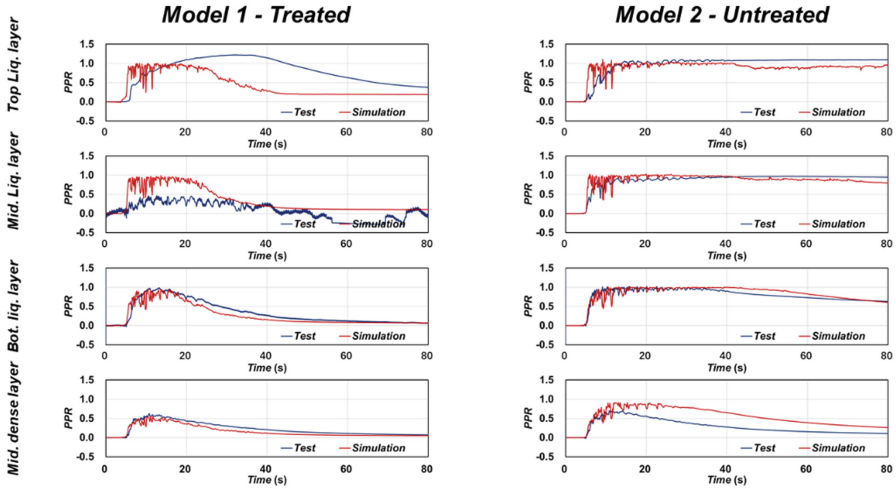
Fig. 4. The numerical and test results of excess pore pressure ratio (r_u) time histories at various depths in both treated and untreated sides.
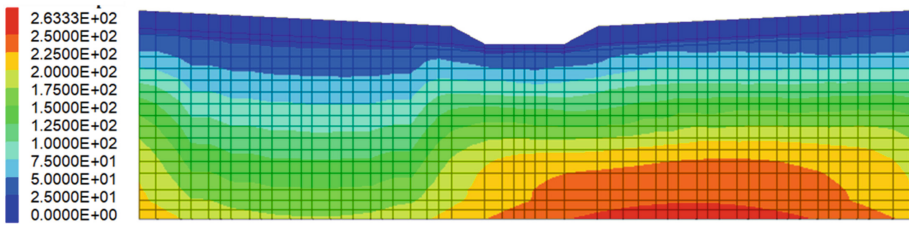

Fig. 5. Contour of excess pore pressure of the model ($t = 40\,\text{s}$)

3.2 Influence of Granular Columns on Ground Displacement

Figure 6 compares the measured and numerically computed horizontal and vertical displacement time histories at the ground surface on both treated and untreated sides. The horizontal displacement are measured at the toes of two slopes, while the vertical displacements are measured at the top. Notable reduction of horizontal displacements in the treated slope in both test and simulation highlights the effectiveness of granular columns. This was due partly to the added shear resistance and partly to the faster dissipation of excess pore pressures [5]. The test results show a clear decrease in the settlement in the side treated with granular columns ($A_r = 20\%$) [6].

The numerical model underestimates the vertical settlement, especially for the untreated side. This deviation is likely due to the selection of model parameters, as the parameters were adopted from previous studies on Ottawa sand, which can be different from batch to batch [10]. However, the overall influence of granular columns is captured.
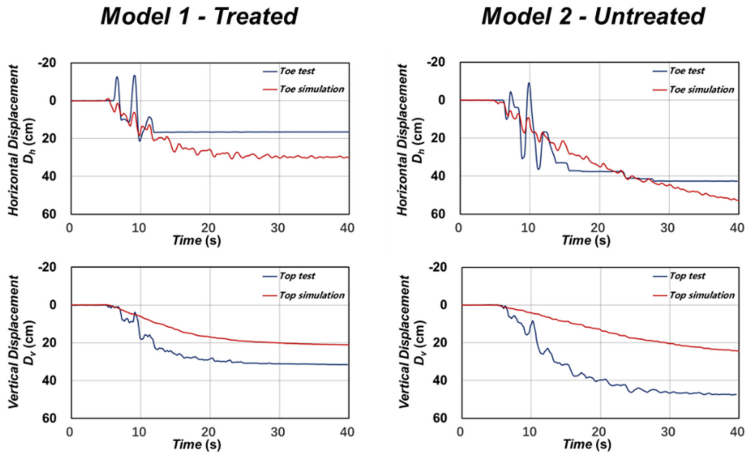
Fig. 6. The numerical and experimental comparisons of displacement time histories at tops and toes on both treated and untreated sides.

3.3 Stress-Strain Analysis

The shear stress-strain curves and effective stress paths in different layers on both treated and untreated sides are shown in Fig. 7 and Fig. 8. Figure 7 indicates that significant shear strain occurs at low mean effective stress values or zero mean effective stress state after initial liquefaction. The shear strain on the treated side is obviously greater than that on the untreated side. Granular columns are shown to be effective in reducing the shear strain in liquefiable soil profile.

As suggested in Fig. 4, where the suppression the build-up of excess pore pressure was indicated, Fig. 8 shows that the installation of granular columns can limit the decrease of effective stress during shaking.
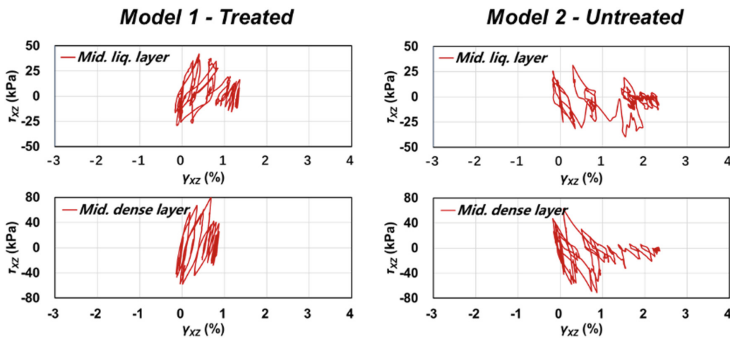

Fig. 7. Comparisons of calculated stress-strain relations ($\gamma_{xz} - \tau_{xz}$) in different layers on both treated and untreated sides.
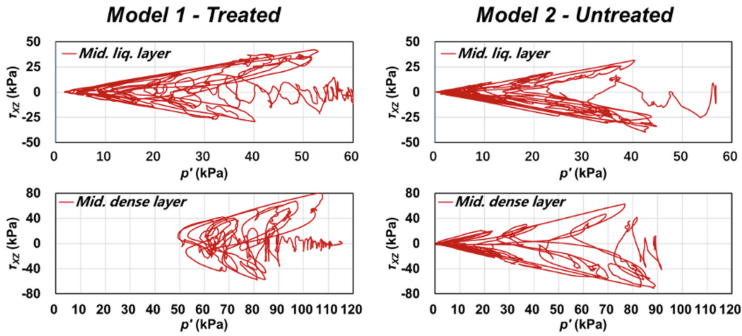
Fig. 8. Comparisons of calculated effective stress paths ($p' - \tau_{xz}$) in different layers on both treated and untreated sides.

4   Conclusions

The numerical simulation of a centrifuge test conducted at the University of Colorado Boulder's 400 g-ton centrifuge facility is reported in this study. A plasticity constitutive model for large post-liquefaction deformation of sand is used, within the FLAC^{3D} finite difference code.

The constitutive model can provide generally good simulation of the excess pore pressure ratio and horizontal and vertical displacements for both treated and untreated ground using a set of previously calibrated model parameters.

The increased excess pore pressure dissipation rate and decreased horizontal and vertical displacements of the treated side suggests the enhancement of drainage. Meanwhile, granular columns can significantly limit shear strain and effective stress decrease in the ground, highlighting the effectiveness of granular columns liquefaction mitigation effects.

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