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Evaluating 2D numerical simulations of granular columns in level and gently sloping liquefiable sites using centrifuge experiments

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ABSTRACT

The response of a layered liquefiable soil profile, with granular columns as a mitigation strategy, was evaluated via numerical and centrifuge modeling. Comparisons were made for a level site containing a single granular column and for a pair of gentle slopes, one of which was mitigated with a network of dense granular columns. The results reveal the abilities and limitations of two state-of-the-art soil constitutive models. All simulations were performed in 2-dimensions using: 1) the pressure-dependent, multi-yield-surface, plasticity-based soil constitutive model (PDMY02); and 2) the bounding surface, plasticity-based, Manzari-Dafalias (M-D) soil constitutive model, both implemented in OpenSees. Numerical model parameters were previously calibrated via element testing. Both constitutive models under-predicted PGA near the surface at different distances from the granular column, but they better predicted spectral accelerations at periods exceeding 0.5 s (particularly M-D). The M-D model generally predicted seismic settlements well, while PDMY02 notably underestimated soil's volumetric compressibility and strains. Both models accurately predicted the peak value and generation of excess pore pressures during shaking for the unmitigated slope, leading to a successful prediction of lateral deformations. However, lateral movement of the treated slope was poorly predicted by both models due to inaccuracies in predicting the dissipation rate in the presence of drains. Both models came close to predicting the performance of gently sloping, liquefiable sites when untreated. But further advances are required to better predict the rate of excess pore pressure dissipation and seismic performance when the slope is treated with granular columns.

1. Introduction

Earthquake induced soil liquefacction can cause extensive damage to buildings, structures, slopes, and retaining walls. Examples include the 1964 Niigata (Japan), 1990 Dagupan City (Philippines), 1999 Chi-Chi (Taiwan), 1999 Kocaeli (Turkey), and 2008 Wenchuan (China) earthquakes among others. Remediation methods are often required to limit liquefaction-induced soil strains to acceptable levels. Dense granular columns reduce soil strains by enhancing drainage and increasing (to different degrees) shear stiffness. In addition, some installation methods lead to significant densification of the surrounding soils, which can help further reduce the potential for generating large excess pore pressures and excessive deformations. Hausler and Sitar [11] compiled over 90 case histories on the performance of improved sites from 14 earthquakes in Japan, Taiwan, Turkey, and the United States. The collected data indicated that drains made of stones, gravel, or sand generally improved site performance in terms of observed deformations.

Beyond case history observations, full scale tests conducted by Ashford et al. [2] have shown that installation of stone columns can notably increase the relative density of the surrounding ground and limit generation of excess pore pressures, while simultaneously providing shear reinforcement. Adalier et al. [1] conducted centrifuge tests to assess the response of granular columns as a liquefaction countermeasure in non-plastic silty soils. They showed that granular columns can reduce net seismic settlements in silty deposits, particularly under shallow foundations.

Numerical simulations may be used to evaluate the generation and dissipation of excess pore pressures, accelerations, and deformations of liquefiable, level or sloping sites when treated with dense granular columns. Previous numerical studies of the response of treated sites have used both two- and three-dimensional (2D and 3D) approaches. The program FEQ-Drain [22], for example, models a unit cell under 3D axisymmetric conditions. But it does not compute lateral soil deformations in slopes. Effective stress, coupled, 2D, dynamic simulations were used by Seid-Karbasi and Byrne [29] to investigate the

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development of excess pore pressures and deformations in sloping sites with a low-permeability barrier, and the effectiveness of drains under such conditions. Elgamal et al. [8], on the other hand, performed a 3D numerical parametric study to evaluate the effectiveness of liquefaction mitigation through granular columns and pile-pinning approaches. Results showed that such methods could be effective in reducing lateral displacements by enhancing drainage and shear reinforcement. Rayamajhi et al. [26,27] subsequently evaluated the influence of granular columns through 3D, nonlinear, finite element simulations. The results showed that dense granular columns may be effective in reducing lateral spreading of gentle slopes, even if liquefaction triggering is not prevented. Later, Howell et al. [14] analyzed lateral spreading in gently sloping sites treated with prefabricated vertical drains (PVDs) using 2D, fully-coupled finite element models, which could capture the 2D rotational modes of deformation experienced by the slopes considered. However, the capabilities and limitations of different soil constitutive models in capturing the influence of granular columns on slopes have not been sufficiently and systematically evaluated based on physical model studies. This is a necessary step before these models can be used in engineering design.

In summary, field case histories are insightful, yet limited in quality (due to lack of instrumental recordings) and quantity for mitigated conditions. Full-scale tests can demonstrate the complexities of soil response under realistic conditions (e.g., pressure, heterogeneity, fines content, mitigation construction techniques, etc.), but their cost and logistics are often limiting. Centrifuge experiments can simulate realistic stresses in a scaled model and subject it to realistic (albeit typically 1D horizontal) earthquake loads in a cost-effective manner. Layering in soil can be simulated, and the results can provide critical insights into the underlying mechanics and help validate numerical simulations. However, realistic soil heterogeneities and complexities as well as installation and construction processes may be difficult to recreate in centrifuge. Therefore, for example, densification caused by the installation of granular columns under increased gravity is often not captured in centrifuge. Fully-coupled, effective stress numerical simulations with nonlinear elasto-plastic soil constitutive models (if well calibrated and validated) can provide insight into the effects of various liquefaction remediation techniques on slopes and structures in terms of the key engineering demand parameters of interest. However, validation through comparison with physically obtained measurements is necessary, if results are to be relied upon.

In this paper, we evaluate the predictive capabilities and limitations of two different state-of-the-art, nonlinear, elasto-plastic soil constitutive models appropriate for modeling liquefaction and employed in 2D using the OpenSees finite element platform, based on their comparison with centrifuge experimental results. The simulations are performed in 2D to provide guidance on the limitations and capabilities of a practical numerical tool. The numerical results presented here are Class-C predictions (i.e., [18]), in that they were performed after the experiment, but the modeler did not have access to the centrifuge results other than the recorded base motions. The simulations were performed using: 1) the pressure-dependent, multi-yield-surface, plasticity-based soil constitutive model (PDMY02) developed and implemented in OpenSees by Elgamal et al. [9] and Yang et al. [33]; and 2) the bounding surface, plasticity-based soil constitutive model developed by Dafalias and Manzari [6], here referred to as M-D, implemented in OpenSees by Ghofrani and Arduino [10]. The soil model parameters were previously calibrated using a series of monotonic and cyclic, drained and undrained trixial tests as well as a free-field centrifuge test involving the same soil types and conditions used in this study (detailed by Ramirez et al. [24,25]).

The results of the numerical study are compared to results from two centrifuge experiments performed by Badanagki et al. [4]. Each test measured the response of a layered soil profile including a liquefiable layer of clean sand overlain by a thin silt cap. The first test comprised a single granular column at the center of a level site, to evaluate its influence on acceleration, pore pressure, and settlement patterns at different radial distances during 1D, horizontal earthquake loading. The second test contained a network of granular columns on a gently sloping site.

Appropriate adjustments were made to convert soil's hydraulic conductivity from 3D (axisymmetric) flow conditions to 2D plane strain in the simulations involving granular columns. The numerically computed response was compared to experimental measurements in terms of lateral and vertical displacements, net excess pore pressures during and after shaking, and accelerations developed in gentle slopes with and without granular columns. Overall, this study reveals the strengths and weaknesses of two state of the art soil constitutive models and one numerical platform in modeling the effectiveness of granular columns as a liquefaction countermeasure in a level and gently sloping, layered site. This understanding is essential for future planning of these models in parametric studies, and the design of liquefaction mitigation using granular columns that improve the site's overall performance.

2. Centrifuge experiments

Two centrifuge experiments were conducted at the University of Colorado Boulder's (CU) 400 g-ton (5.5 m-radius) centrifuge facility to investigate the influence of dense granular columns on site performance when installed in level and gently sloping, layered, liquefiable ground [4]. The first experiment (Test 1) simulated the response of a unit granular column in a level site. The second test (Test 2) simulated gently sloping liquefiable soils with and without granular columns. Figs. 1 and 2 show the elevation and plan view geometry and instrumentation layout of the two tests. The models were spun to 70 g of centrifugal acceleration and subject to a series of 1D horizontal earthquake motions in flight, in the same order. All the results presented in this paper are in prototype scale, unless stated otherwise.

Ottawa and Monterey sand layers were prepared by air pluviation using the automated pluviator at CU. From the bottom, the soil profile

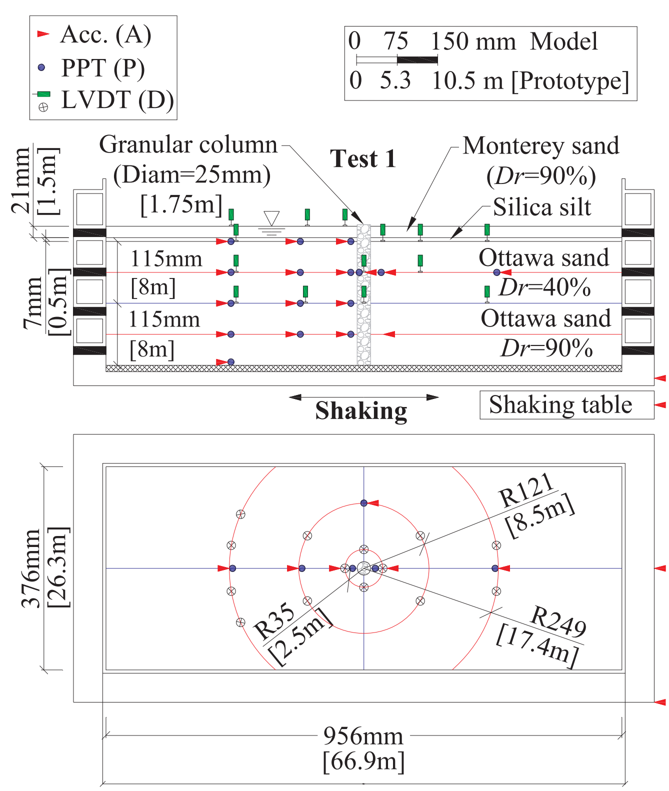

Fig. 1. Schematic drawing (elevation and plan view) and instrumentation layout of Test 1 with one drain.