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Numerical simulation of improvement of a liquefiable soil layer using stone column and pile-pinning techniques

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ABSTRACT

Structures in seismically active regions are vulnerable to failure due to excess pore pressure generation and the liquefaction potential of underlying deposits, especially when no ground improvement is conducted. The risk of liquefaction and associated ground deformation can be reduced by various ground improvement techniques, such as the stone column (SC) and pile-pinning methods. In this paper, the effects of SCs and pile-pinning on reducing the potential for liquefaction during earthquakes are investigated parametrically, applying three-dimensional finite element (FE) simulations using OpenSeesPL. Saturated loose sand and silt layers are subjected to two realistic destructive events with different characteristics. The objective of this study is to assess the effectiveness of the SC and pile-pinning methods on the basis of several different factors, including area replacement ratio (A_{rr}), soil and SC permeability, ground slope angle, pile/SC diameter, mass of the superstructure and earthquake characteristics. This parametric study evaluates the effect of each of these factors on soil acceleration, lateral displacement, excess pore pressure and shear stress–strain. The results are qualitatively in agreement with centrifuge test results and field observations. The numerical results provide a means of representing the seismic performance of the SC and pile-pinning at sites with liquefaction-induced lateral spreading and can be helpful in practical engineering applications.

1. Introduction

The lateral spreading of mildly sloping ground and the liquefaction induced by earthquakes can cause major destruction to foundations and buildings, mainly as a result of excess pore water pressure generation and softening of the subsoil. The risk of liquefaction and associated ground deformation can be reduced by various ground improvement methods, including densification, solidification (e.g., cementation), vibro-compaction, drainage, explosive compaction, deep soil mixing, deep dynamic compaction, permeation grouting, jet grouting, pile-pinning and gravel drains or SCs [1,2]. Two well-known methods, the stone column (SC) and pile-pinning methods are discussed and compared in this paper. The use of SCs has proven to be an economical and technically viable ground improvement technique for construction on soft soils and has been successfully used in the foundations of structures such as oil storage tanks, earth embankments and raft foundations. SCs have been effectively used to mitigate liquefaction in sand, but might be typically much less effective in silty sands or soils with a high content of fines [3,4]. In contrast, pile-pinning appears to be equally effective for sand and silt strata [5]. This paper proposes the use of numerical simulations to evaluate lateral displacement and excess pore pressure in the presence of an improvement method. The research conducted for this study focused on the SC and the pile-pinning methods with respect to the effectiveness of each method in keeping permanent seismic deformation to sufficiently low levels in sandy and silty soils.

2. Literature review

Geotechnical earthquake engineers conduct extensive research to understand and characterize various SC and pile-pinning applications and to assess their effectiveness as liquefaction countermeasures, through field case histories [6–10], field tests [11,12], experiments [13–20] and numerical simulation [5,21,22]. Use of SCs is a rather recent development compared to more traditional soil densification approaches [23]. Use of SCs as a liquefaction mitigation procedure was first studied by Seed and Booker [24]. Since then, the SC technique has attracted the attention of leading researchers (e.g., Refs. [25–27]). Full-scale tests of SC installations in loose cohesionless soils by Ashford et al. [11] showed that excess pore water pressure generation was reduced and the rate of pore pressure dissipation was increased by SC installation. Adalier et al. [15] conducted a series of highly instrumented dynamic centrifuge model tests to evaluate the effectiveness of SCs in non-plastic silty deposits. The study was focused on the possible stiffening effect of SCs, rather than on

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Nomenclature

M_w	Moment magnitude of earthquake
c_1	Contraction parameter
T_p	Predominant period
φ_{PT}	Phase transformation (PT) angle
t_p	Time of peak ground acceleration
d_1, d_2	Dilation parameters
PGA	Peak ground acceleration
k_s	Soil permeability coefficient
D_{5-95}	Significant duration
k_{sc}	Stone column permeability coefficient
N_c	Number of significant excitation cycles
A_{rr}	Area replacement ratio
I_a	Arias intensity
S	Distance (spacing)
ρ	Mass density
D	Diameter
G	Low-strain shear modulus
α_f	Ground slope angle
Dr	Relative density
d	Depth
φ	Friction angle
EI	Bending stiffness
ψ	Dilation angle
D_H	Maximum lateral displacement
γ_y	Liquefaction yield strain
EPP	Excess pore pressure

improved drainage and densification. Acceleration and EPP data indicated an overall stiffer response during shaking in modeled foundation materials as remediated by SCs. The drainage effects of the SC method remain debatable and SCs are not always considered to contribute to liquefaction mitigation.

The pile-pinning method was first implemented in the United States as a result of the seismic safety evaluation of Sardis Dam [28]. The pile-pinning effect is now recognized as a legitimate remediation option when bridge or wharf structures built on pile foundations are located in areas susceptible to liquefaction-induced lateral displacement [29,30]. The effect of the nature of earthquakes on pile performance in liquefiable soils was studied by Liyanapathirana and Poulos [31], using 25 earthquake records scaled to different acceleration levels. It was shown that the Arias intensity and the natural frequency of the earthquake ground motion have a significant influence on the pile performance in liquefying soil. Gonzalez et al. [32] studied six models in centrifuge experiments, to investigate the effect of soil permeability on the response of end-bearing single piles and pile groups subjected to lateral spreading. The results showed evidence of the importance of soil permeability on pile foundation response during lateral spreading in cases where the liquefied deposit reached the ground surface and suggested that bending response may be greater in silty sands than in clean sands in the field. Centrifuge testing [33] and field case histories [10] of the effect of liquefaction-induced lateral spreading on pile foundations in the presence of superstructure loading have indicated that the inertia effect of the superstructure is typically significant at the beginning of shaking when lateral spreading is minimal.

Elgamal et al. [5] conducted three-dimensional (3D) FE simulations using OpenSees [34] with the aid of OpenSeesPL [34], a user interface that simplifies the pre- and postprocessing phases, to evaluate mitigation by the SC and pile-pinning approaches on the basis of a systematic parametric study. They found SC remediation was effective in reducing sand stratum lateral deformation. For a similar stratum with permeability in the silt range, SC remediation was found to be ineffective, regardless of the higher permeability of the SC employed. Pile-pinning appeared to be equally effective for sand and silt strata. In this recent study, Elgamal et al. [5] identified and examined important factors for mitigation of liquefaction-induced lateral deformations including area replacement ratio A_{rr}, soil and SC permeability. Investigation on the effects of the other key parameters and the complex interactions between these parameters can be a valuable tool to gain new insights for improved seismic design and construction. Hence, in this paper, the effects of several key parameters (e.g. A_{rr}, soil and SC permeability, ground slope angle, pile/SC diameter, mass of the superstructure and ground motion characteristics) and their interactions on the seismic responses were identified and studied through 3D simulations using OpenSeesPL [34].

3. Numerical simulations

Soil properties, analysis approach and constitutive equation in this study are in accord with earlier research by Elgamal et al. [5,34], which are briefly described in this section.

3.1. Model geometry, soil properties and motion characteristics

The soil forming the geotechnical profile and its mechanical properties are described, beginning from the surface of the ground and proceeding to the bottom of the profile. A series of 3D numerical simulations have been performed to gain insight into the seismic performance of the pile-pinning and SC in medium-saturated Nevada sand soil and silt strata (Dr of approximately 40%) with a thickness of 10 m above the bedrock (Fig. 1).

To examine characteristics of motions effects, different models have been subjected to the El Centro (1940) and Loma Prieta (1989) earthquakes (shown in Fig. 2) with various scaled peak ground accelerations. Characteristics of these earthquakes are presented in Table 1. The foregoing earthquake time histories were chosen for two main reasons:

(a) They have different acceleration time history waveforms (e.g. the El Centro (1940) excitation has 14.5 significant cycle of excitation, while the Loma Prieta (1989) excitation has almost 5.8 significant cycles).
(b) They have been related to large ground failures and extensive liquefaction phenomena.

The influences of the axial load transfer mechanism from the pile and SC to the surrounding soil during the loading process are analyzed and the results are compared with the free field. In addition, the inclination effect of a saturated sand layer on the mechanism of lateral displacement was investigated for the same conditions. SC permeability is presumed to vary from $k_{sc} = 0.01-1.0\ m/s$ for the purpose of evaluating its influence on the seismic response of SC.

In the remediated cases, the area replacement ratio A_{rr} is conventionally defined as the area of the SC or pile (A_r) to the tributary area A.

$$A_{rr} = \frac{A_r}{A} = \frac{\pi D^2}{4S^2}$$

The effects of various A_{rr} values on lateral displacement are considered. In addition, diameter effects are investigated, keeping A_{rr} constant. For pile-pinning, the same geometric configuration was used as that of SC (Fig. 1): a 0.6-m-diameter reinforced concrete pile and a representative bending stiffness that considers the pile level of deformation $EI = 1.27 \times 10^5$ kN m^2 (American Concrete Institute, ACI, 2008) [5]. Rigid beam-column connections, normal to the pile