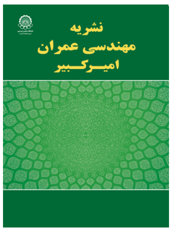

Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 53(7) (2021) 675-678
DOI: 10.22060/ceej.2020.17657.6639

Using Pile Group to Mitigate Lateral Spreading in Uniform and Stratified Liquefiable Sand Strata: Three-Dimensional Numerical Simulation

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ABSTRACT: According to reports from past earthquakes around the world, the phenomenon of liquefaction is one of the main hazards of earthquakes that causes damage to structures and infrastructures. The risk of liquefaction and associated lateral spreading can be reduced by various ground improvement techniques, 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. In this research, the effects of pile groups on reducing the potential for liquefaction during earthquakes are investigated parametrically, using three-dimensional finite element (FE) simulations via OpenSees. Saturated uniform and stratified loose sand are subjected to two realistic destructive events with different characteristics. A multi-yield-surface plasticity model, Drucker–Prager yield criterion, is considered for the dynamic analysis conducted in this study based on constitutive laws applicable to all types of soils. The objective of this research is to assess the effectiveness of the pile group based on several different factors, including area replacement ratio (A_rr), piles diameter, number of piles, thickness and position of liquefiable soil, and earthquake characteristics. This parametric study evaluates the effect of each of these factors on soil acceleration, lateral displacement, and excess pore pressure. The results showed that the lateral displacement and excess pore pressure decrease, as the area replacement ratio, number, and diameter of the pile increase. Besides, the responses of the saturated stratified sand strata are not only dependent on the thickness of the liquefiable layer but are also highly influenced by its position. The presence of a liquefiable layer at lower depths, although acting as an isolate relative to the acceleration, can increase lateral displacements. Also, according to the results, there is an appropriate correlation between the variations of lateral displacement rate of piles and soil and earthquake parameters including Arias intensity, the time corresponding to the PGA, and the number of significant excitation cycles. Therefore, the results of this study may be applicable for other earthquakes.

Review History:

Received: Jan. 05, 2020
Revised: Jan. 14, 2020
Accepted: May. 15, 2020
Available Online: Jul. 13, 2020

Keywords:

Liquefaction
Pile groups
Liquefiable soil layer
3D numerical simulation
OpenSees

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 [1]. One of the effective methods to reducing the risk of liquefaction and associated ground deformation in saturated sands is the pile-pinning technique. The soil near the pile pinning tends to respond as undrained, and a larger lateral resistance is mobilized due to the dilative response of liquefied soil. Many attempts have been made in recent decades to study the behavior of a pile in liquefied soil, using various experimental techniques including dynamic centrifuge experiments, shaking Table tests, and full-scale field tests as well as various numerical modeling methods [1-3]. This study focuses on the effects of pile-pinning on the seismic response of saturated soil based on numerical simulation. Additional simulations considering a wider range of values for the area replacement ratio, pile diameter, liquefiable layer thickness, situation of very loose sand, and input motion parameters were conducted to fully characterize the seismic response of saturated uniform and stratified sand deposits in the presence of piles and compared together.

2. NUMERICAL SIMULATIONS

Generally, 72 numerical simulations have been performed using the open-source computational platform OpenSees [4] to gain insight into the seismic performance of the pile-pinning in 10-m-thick mildly inclined (4°) saturated uniform and stratified sand soil above the bedrock (Fig. 1).

The physical and mechanical properties of the soil layers and the pile are presented in Table 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 0.25 g scaled peak ground accelerations.

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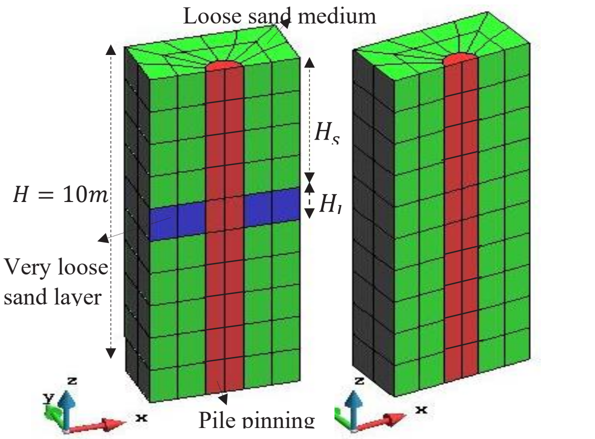

Fig. 1. 3D view of soil mesh and pile pinning, Right side: Uniform saturated sand, Left side: Stratified saturated sandy soil

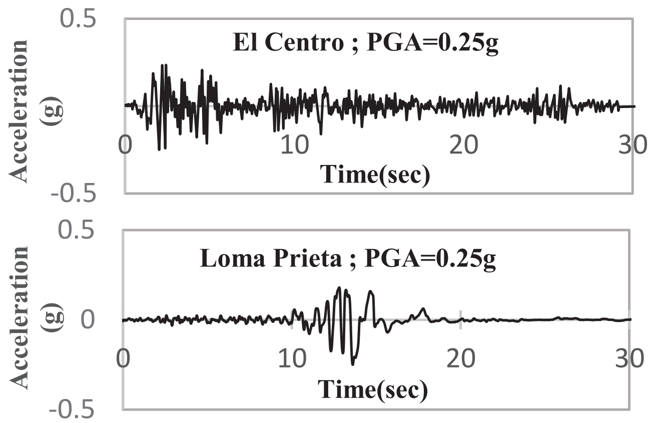

Fig. 2. Horizontal acceleration history for the El Centro (1940) and Loma Prieta (1989) with scaled PGA of 0.25 g, of the input events

Table 1. Soil and pile model parameters

Soil Parameters	Medium	Very Loose
Mass density, ρ	2000 kg/m^3	1700 kg/m^3
Permeability coefficient, k	$6.6 \times 10^{-6} m/s$	$10^{-5} m/s$
Shear modulus, G	100 MPa	55 MPa
Bulk modulus, B	300 MPa	150 MPa
Friction angle, φ	35°	29°
Phase transformation (PT) angle, φ_{PT}	26.5°	29°
Contraction parameter, $c1$	0.21	0.35
Dilation parameter, d	0.6	0
Dilation parameter, $d2$	0.3	0
Pile Parameters		
Mass density	2400 kg/m^3	
Elastic modulus	20000 MPa	
Poisson's ratio	0.3	

The effects of various $A_{rr} = \pi D^2/4S^2$ (D and S are pile diameter and spacing between the pile centers, respectively) [1, 3] values on lateral displacement are considered. In addition, diameter effects are investigated several piles pinning configurations (1×1, 2×2, and 4×4). For more detail, refer to Ref [5]. Besides, In the case of remediation of stratified medium sand, two dimensionless parameters have been defined to investigate the effect of the very loose layer thickness and its position on the lateral deformation as follow:

$$H_{lr} = H_l/H, \quad H_{sr} = H_s/H \tag{1}$$

Where H is the height of soil medium, H_s is the distance from the ground surface to the very loose sand layer, and H_l is the thickness of the liquefiable very loose layer (See Fig. 1).

As mentioned, all of the simulations conducted were developed and executed using the open-source computational platform OpenSees [4] based on u-p formulation. In 3D, the soil domain is represented by 8-20 node, fully coupled (solid-fluid) brick elements. The multi-yield-surface plasticity [6] model was chosen for the analysis conducted in this study. The analysis framework and its assumptions, boundary conditions, and constitutive law for saturated soil response were considered according to the Refs [7].

3. RESULTS AND DISCUSSION

To investigate the effect of the number of piles on the generation and dissipation of pore water pressure, the time history of excess pore water pressure in surrounding piles 1×1 - 2×2 - 4×4 for depths of 2 and 8 m is shown in Fig. 3. According to Fig. 3, as the number of piles increases, the maximum EPP decreases and disappears sooner, which is due to the increase in system stiffness and the increasing effect of the dilatancy phenomenon. In other words, increasing the stiffness of the system reduces the displacement (not shown here) of the surrounding soil, thereby reducing the incremental process of excess pore water pressure. Also, the result is shown that with increasing H_{lr} and H_{sr}, the lateral displacement of the pile head increases.

4. CONCLUSION

In this paper, the behavior of the pile group with different configurations of 1×1 - 2×2 - 4×4 in two cases (uniform saturated sand strata/stratified saturated sand layer) has been evaluated under two earthquake records. The main important conclusions drawn from the present study are as follows: Generally, the lateral displacements were amplified as the

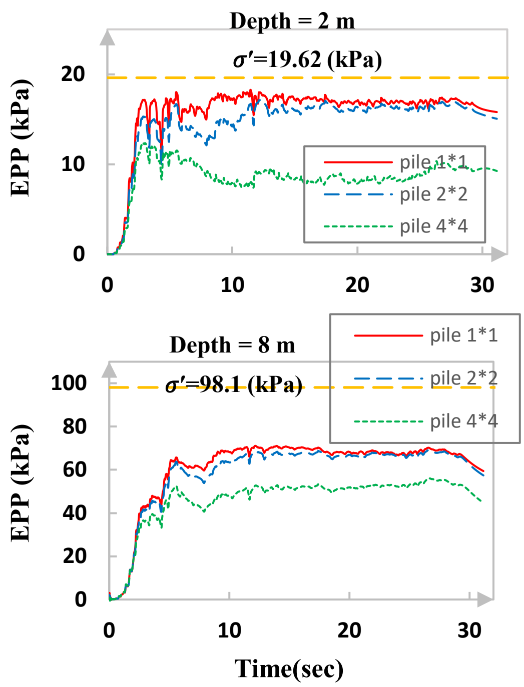

Fig. 3. Time history of excess pore water pressure in surrounding piles 1×1 - 2×2 - 4×4 for different depths

Arias intensity in an event increased. The variations of lateral displacement rate are related to rates of Arias intensity (not shown). The maximum excess pore pressure ratio has been observed in the very loose sandy soils, due to the contractile behavior of this type of sand. In stratified saturated sand soils, when a very loose layer with a constant thickness is placed at the deeper depth, excess pore water pressure in the upper layers of the soil decreases (not shown). However, in contrast to excess pore water pressure, the displacement of the pile head increases due to the increase in the lateral force of the liquefied soil at a lower depth, which in turn leads to an increase in rotation at the same height from the pile and eventually increases horizontal displacement. Therefore, it can be mentioned that in the designs, it is not possible to make a decision alone based on only one of the outputs (e.g., displacement, excess pore water pressure in the soil, or bending moment of the along pile).

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HOW TO CITE THIS ARTICLE

A. Asgari, F. Ranjbar, H. Akbarzadeh Bengar, Using Pile Group to Mitigate Lateral Spreading in Uniform and Stratified Liquefiable Sand Strata: Three-Dimensional Numerical Simulation, Amirkabir J. Civil Eng., 53(7) (2021) 675-678.

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