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Numerical Modeling of the Effects of a Group of Micro piles in Liquefiable Soils

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ABSTRACT

As micro piles, small-diameter (d < 300 mm) piles installed in problematic liquefiable soils are widely used in seismic areas, studying their behavior during an earthquake is of great importance. To validate the numerical modeling accurately, this study used the finite difference method to investigate the liquefaction phenomenon with the help of the FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) Software and compared the results with those of Test No. 1 of the VELACS international project. Next, to check the efficiency of micro piles in liquefiable soils, such influential parameters as their number, presence/absence of superstructures on them, their spacing-to-diameter ratio (s/d) were investigated, and the results indicated that increasing their number reduced the excess pore water pressure. Although the s/d effects were ignorable, smaller spacing (denser), micro piles reduced the settlement more in the presence of live loads.

Keywords: **Micro pile, Finite difference method, Liquefaction, Seismic load**

1. INTRODUCTION

Liquefaction is a problem that threatens the stability of foundations on saturated sands, and one way to increase the soil resistance against it is by using micro piles. They have diameters smaller than 300 mm and are more advantageous than piles [1]. As they are often reinforced with light steel and cement grout injection, they not only resist settlement as bearing elements but also improve the mechanical features (strength and behavior) of the surrounding soil due to the mentioned injection [2]. Micropiles are, in fact, expected to reduce the risk of liquefaction by increasing the soil stiffness, reducing its movements, and, hence, reducing the cyclic shear strains [3]. The behavior of micro piles in liquefiable soils depends on such parameters as the loading type, frequency of incoming waves, and the surrounding soil behavior, which is assumed to be elastic in many related studies [4-7]. However, studies on recent devastating earthquakes – Kobe (1995), Loma Prieta (1989), Kocaeli (1999) – show that assuming nonlinear behavior for surrounding soils gives better results in deep foundation (micropile-pile) designs in seismic areas.This study is aimed to examine the dynamic

behavior of groups of micro piles in liquefiable soils studied by many researchers through physical and numerical models and field studies. In physical modeling, e.g., (1g) shaking table and (ng) centrifuge, many researchers have used small-/large-scale models to study the seismic behavior of single/group of micropile(s) both vertically and obliquely under 0-20° angles (with respect to normal), in both dry and saturated soils, by changing the effective parameters and have checked their performance in improving the liquefaction potential [2, 3, 8-11]. Some researchers have used finite element and finite difference methods to study the bending moment of micro piles in dry soils [12-16], and some have used finite element and physical modeling with (ng) centrifuge to study how micro piles reduce the liquefaction potential of non-cohesive soils [17-19], and a few have used case studies to examine how micro piles improve soils to prevent liquefaction [20, 21, 22]. As examining the above research show that no specific numerical study has been done to see how micro piles behave in liquefiable soils, this research first used the FLAC3D Software for the numerical modeling validation through the results of VELACS international project Test 1 model and then analyzed the effects of the performance of micro piles by modeling 4 different groups of them under long/short (scattered/dense) spacing with/without superstructures.

2. METHODOLOGY

2.1. VELACS TEST 1 MODEL SPECIFICATIONS

The VELACS project was done in 1993 in the centrifuge physical model framework in 9 different modes to examine the soil liquefaction mechanism. In this project, validation is checked by VELACS international project Test 1 class B (with a vertical acceleration of 50 g) that uses a uniform, 40% dense layer of saturated Nevada sand, the parameters of which are listed in Table 1 [23]. Here, the dynamic load is applied at the bottom of the laminar test box with an acceleration history including 20 cycles with a frequency of 100 Hz and a maximum acceleration of 11.75 g.

Table 1. Characteristics of the 40%-dense Nevada sand [23]

Parameter	Porosity	Dry density	Soil cohesion	Angle of internal friction	Elasticity modulus	Standard permeability number	Permeability coefficient	Poisson's ratio
Unit	-	Kg/m^3	kPa	degree	MPa	-	m/s	-
Amount	0.42	1500	0	30	10	7	6.5e-5	0.3

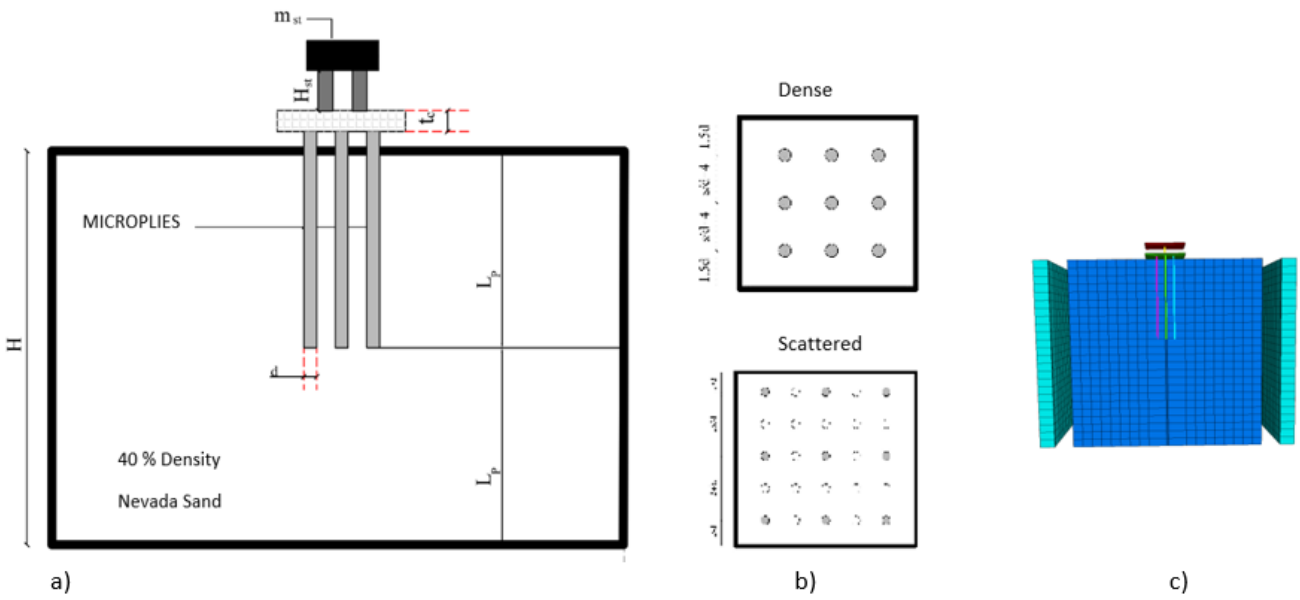

Figure 1. The initial model considered for numerical modeling, (a) Overview of modeling, (b) Arrangement of micro piles, (c) Meshed model in the software

2.2. CONVERTING THE PHYSICAL CENTRIFUGE MODEL INTO THE INITIAL MODEL

Considering the physical modeling vertical acceleration, a 1:50 scale factor was used to convert the initial model into a physical model; dimensions of the initial model were taken (according to Table 2) to be 23, 16, and 10 m in the x, y, and z directions, respectively, and the dynamic loading was applied to the bottom of the initial model with an acceleration history (Fig. 6) with a frequency of 2 Hz, a maximum acceleration of 0.235 g and a vertical acceleration of 0. Dimensions of the initial model and its applied acceleration history were calculated according to the scale factors of the ng-model (Table 2) [24].

Table 2. Scale factors used in the centrifuge test [24]

Parameters	Scale factors λ=50	Small-scale physical model	Initial model
Dimensions	λ	20×45.72×32 cm	10×23×16 m
Density	1	40%	40%
Acceleration	1/λ	11.75g	0.235g
Frequency	1/λ	100 Hz	2Hz
Stiffness	1	10 MPa	10 MPa

2.3. Selecting the behavioral model and model damping

The finite difference method uses the Mohr-Columb behavioral model to define soil materials' plastic deformations, and the Finn elastoplastic behavioral model, presented by Byrne (1991) [27], for the liquefaction modeling, according to Eq. (1):

$$\frac{\Delta\varepsilon_{vd}}{\gamma} = C_1 \exp(-C_2 \left(\frac{\varepsilon_{vd}}{\gamma}\right)) \quad (1)$$

where, $\Delta\varepsilon_{vd}$ is the volumetric strain reduction growth, γ is the cyclic shear strain range and C_1 and C_2 are constants showing the changes in the volume and density of the soil. In the dynamic analyses, this modeling uses the local damping, according to Eq. (2):

$$\alpha_L = \pi \times D \quad (2)$$

where, α_L is the coefficient of local damping and D is 5% of the critical damping, which, compared to local damping, shortens the analyses time due to less calculations than other types of damping, and operates independently of the system natural frequency. The centrifuge boundary conditions are closed on the sides and hard on the bed for modeling. After dynamic analyses under the above conditions, the results of the numerical modeling were compared with those of the VELACS Test 1 physical centrifuge model; in Figures 2-5 that show the results in the form of excess pore water pressure, the horizontal line shows the null effective stress zone at the studied depth, which, compared to the graphs of the excess pore water pressure, means that the numerical analyses results are acceptably close to those of the centrifuge model.

2.4. NUMERICAL MODELLING OF THE INITIAL MODEL

As small-scale physical models, such as the centrifuge and shaking Table, are not only time-consuming and expensive but are also weak in simulating and meeting the boundary conditions [25, 26], modeling by numerical methods becomes a necessity. This research has used the FLAC3D finite difference software for the analyses and 0.2 m-dia., 8 m-long concrete micro piles, with an axial stiffness of 629 MN (Table 3), for the modeling. Micropile is modeled as beam elements; the soil is modeled using a brick element; the micro piles-cap connection is rigid, with no connection with the surrounding soil, cap thickness is 1 m, and the center-to-center distance of micro piles is 4 times the micropile diameter. To model the effects of the inertial forces on the dynamic response of the micropiles, use has been made of a 1-DoF superstructure with a mass of 40 tons consisting of two 1.25-m columns; full features of the cap and

superstructure are listed in Table (4). The micro piles-surrounding soil interface is defined by certain elements, the normal shear and bending stiffness of which equal the shear modulus of the soil [14]; Figure (6) shows the history of the acceleration applied to the initial model.

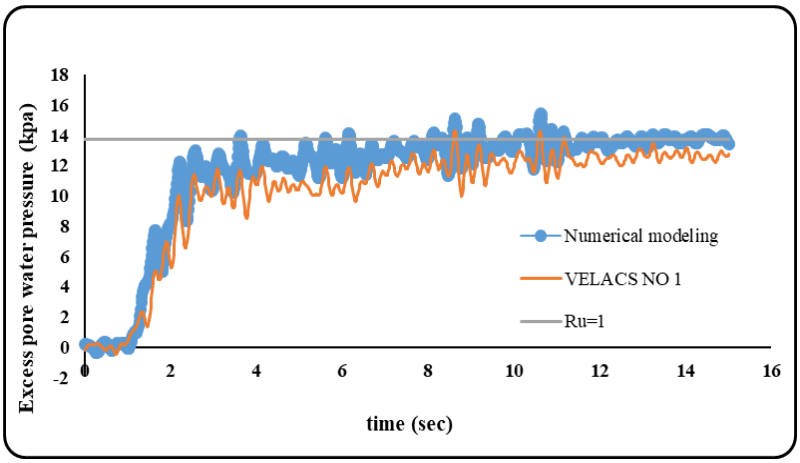

Figure 2. Excess pore water pressure at a depth of 1.5 m

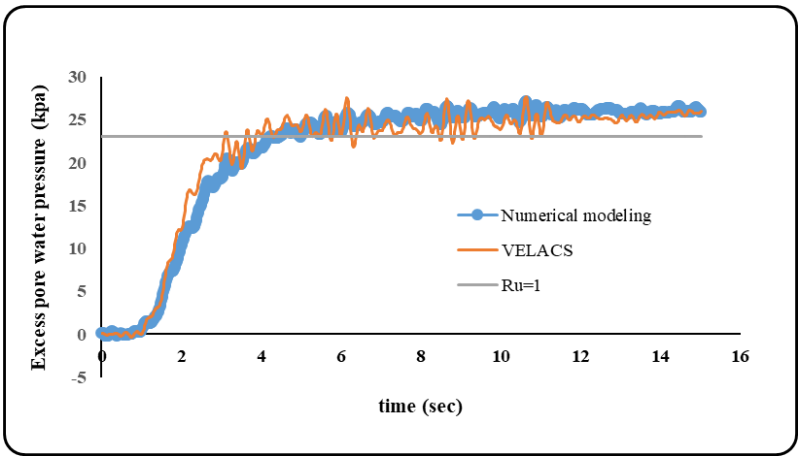

Figure 3. Excess pore water pressure at a depth of 2.5 m

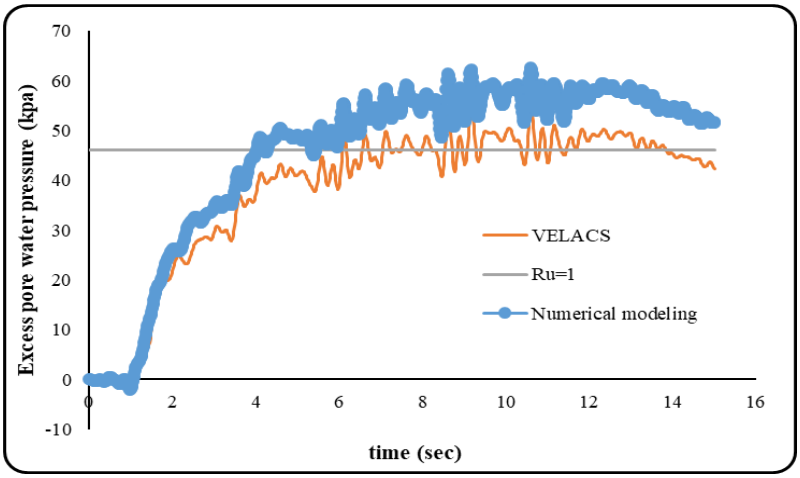

Figure 4. Excess pore water pressure at a depth of 5 m

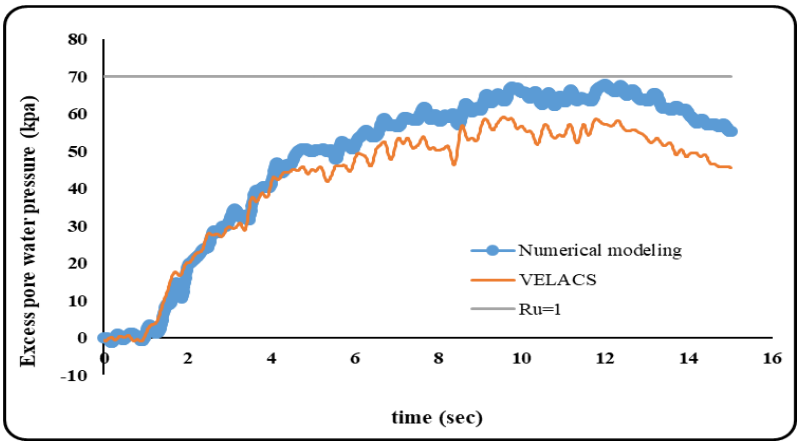

Figure 5. Excess pore water pressure at a depth of 7.5 m

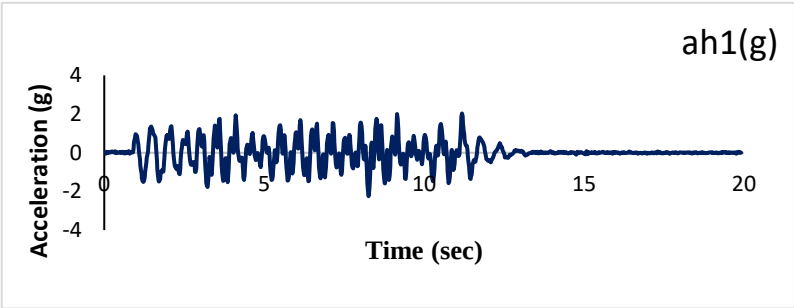

Figure 6. Acceleration map of VELACS Test 1

This modeling has used free boundaries not to let waves enter the model and to reduce the effects of boundary conditions on the sides of the model.

Table 3. Characteristics of the base concrete micropile

Density	Poisson's ratio	Elasticity modulus	Length-to-diameter ratio	Spacing-to-diameter ratio	Diameter	Length
$\boldsymbol{\rho}\ (\boldsymbol{kg/m^3})$	ν	$E\ (N/m^2)$	L/d	S/d	$d_P\ (m)$	$L_P\ (m)$
2400	0.3	2.2e10	40	4	0.2	8

Table 4. Specifications of the base cap

Height	Mass	Density	Poisson's ratio	Elasticity modulus	Thickness	With	Length
$\boldsymbol{H_{st}\ (m)}$	$m_{st}\ (t)$	$\rho\ (kg/m^3)$	ν	$E\ (N/m^2)$	$t_C\ (m)$	$D_C\ (m)$	$L_C\ (m)$
1.25	40	2400	0.3	2.5e10	0.3	3	3

3. RESULTS AND DISCUSSION

3.1. PARAMETERS

This study has used various micropile arrangements with various s/d ratios, with/without superstructure (Fig. 1b), to check the micro pile's efficacy in reducing the soil settlement and excess pore water pressure.

3.2. EFFECTS OF NUMBER OF MICROPILES

To study the effects of the number of micropiles on the excess pore water pressure and soil settlement, this research has used 4 different groups of micro piles all designed based on the data of Table (3). Figures 7-8 show the related results; groups with more micro piles have reduced excess pore water pressure and more settlement in loose soils.

3.3. MICROPILES SPACING EFFECTS

To study the micropiles' spacing (density/dispersion) effects, other parameters were kept constant, and some different-spacing models were designed based on the data of the mentioned Tables. Fig (9) shows the settlement variations for dense and scattered micro piles with different s/d ratios; the results of both cases are quite close and do not improve the liquefaction-induced settlement considerably.

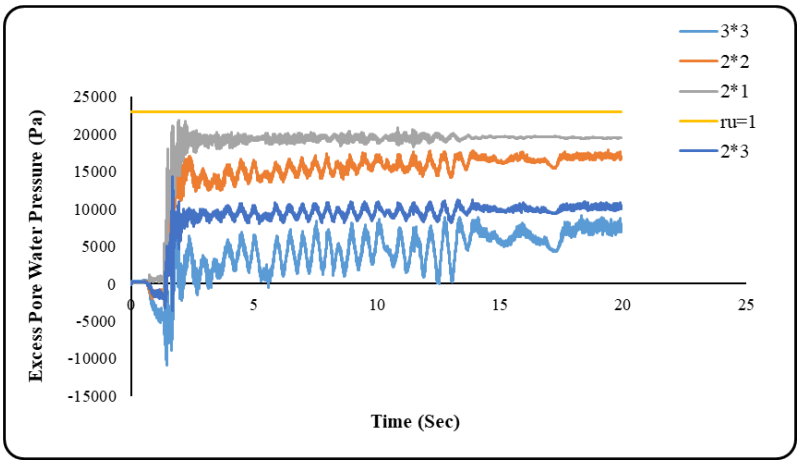

Figure 7. Excess pore water pressure variations for micropile groups at a depth of 2.5 m

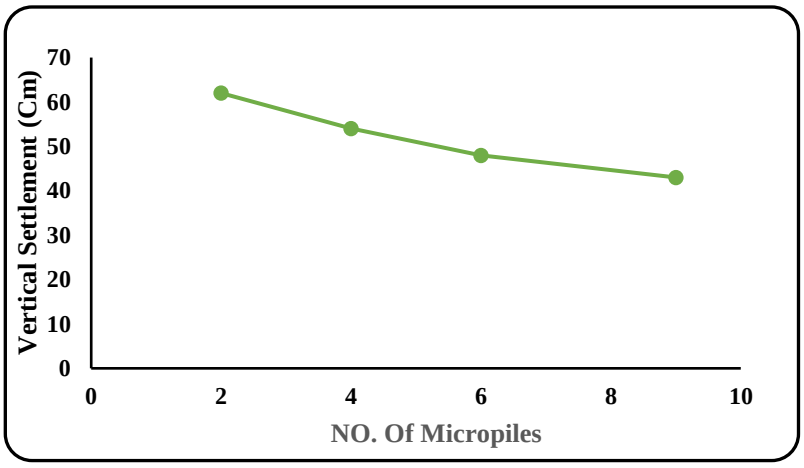

Figure 8. Micropile settlement (with superstructure, s/d = 4)

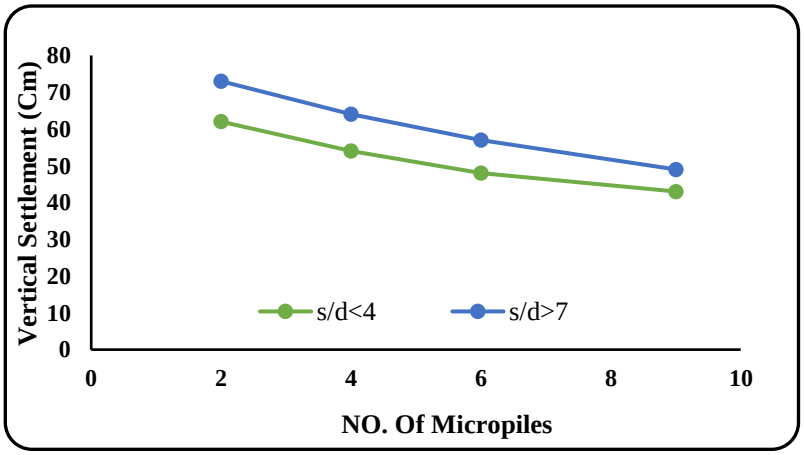

Figure 9. Dense/scattered micropile settlement (with superstructure)

3.4. SUPERSTRUCTURE EFFECTS

Different models with/without superstructure/micro piles were designed based on the data in Table (4) to study how superstructures affected the liquefaction potential; effects of using micro piles with and without superstructures are shown in Figures 10-11, and results of soil settlement with/without using micro piles and superstructures are shown in Figures 12-15. As shown, the effects of using micro piles are more without superstructures than with them, concluding that without superstructures, scattered or dense micropile arrangements do not reduce settlements, but with superstructures, short-spacing (dense) micropile arrangements reduce settlements more than long-spacing (scattered) cases.

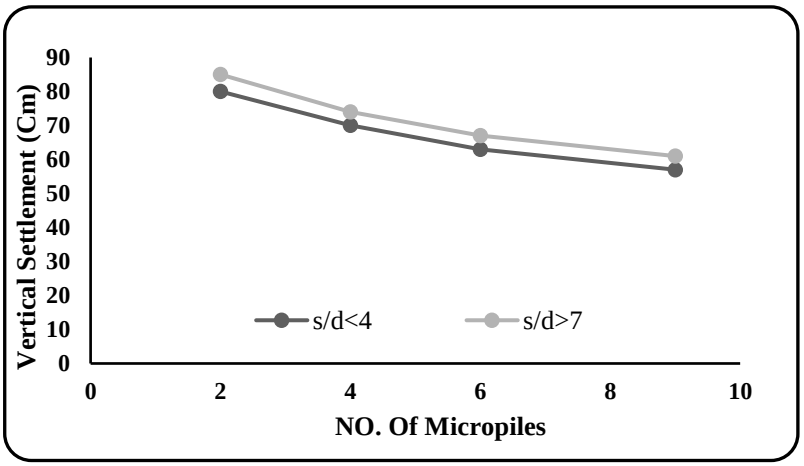

Figure 10. Settlement for dense/scattered micropiles (without superstructure)

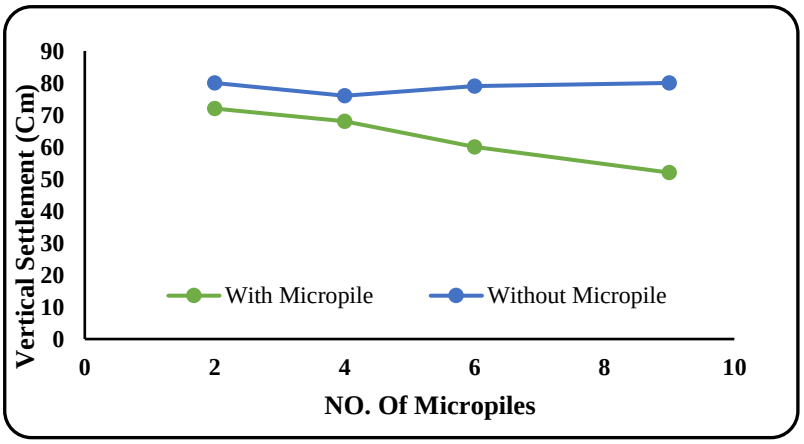

Figure 11. Settlement for the case with/without dense micropiles (with superstructure)

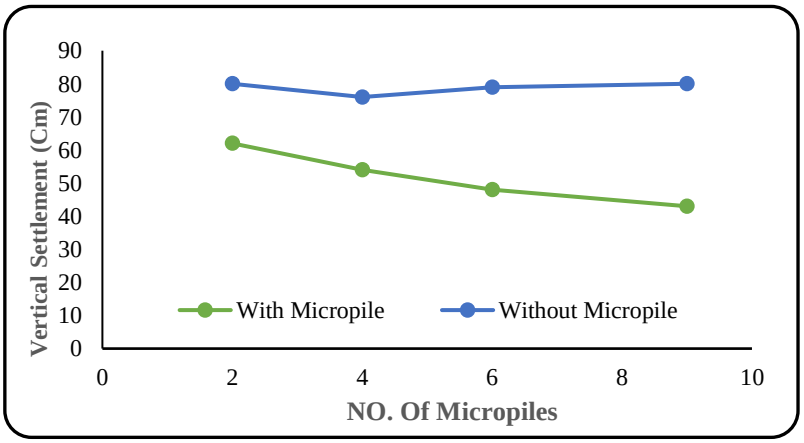

Figure 12. Settlement for the case with/without scattered micropiles (with superstructure)

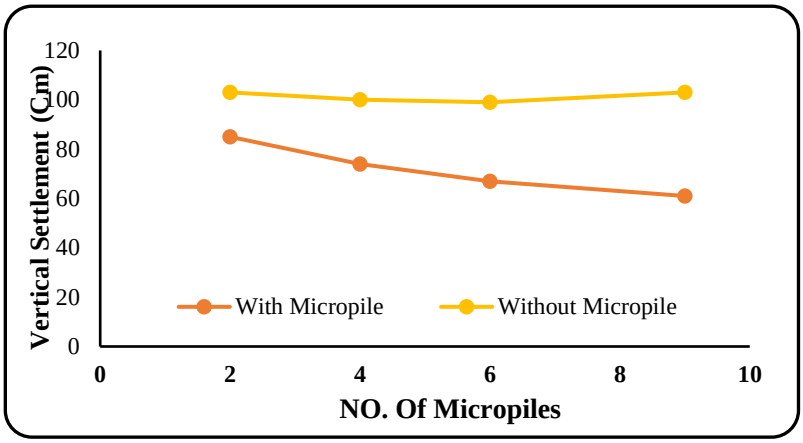

Figure 13. Settlement for the case with/without dense micropiles (without superstructure)

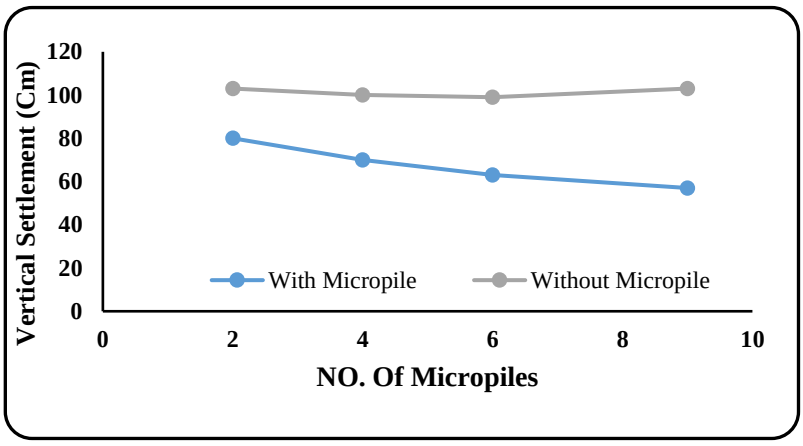

Figure 14. Settlement for the case with/without scattered micropiles (without superstructure)

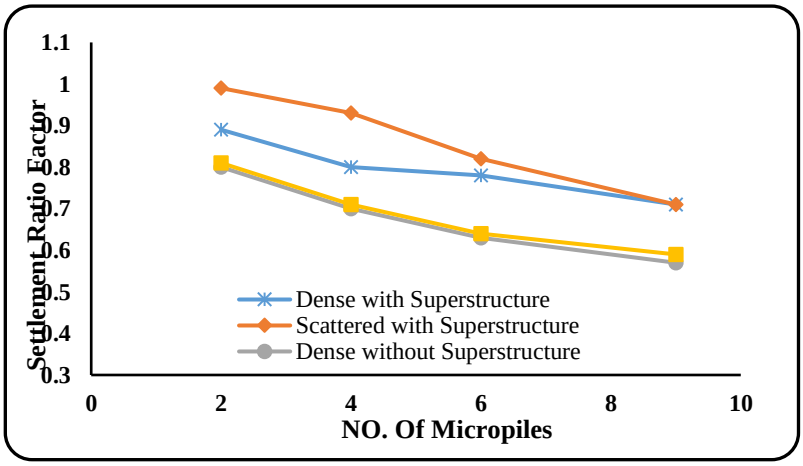

Figure 15. Settlement for dense/scattered micropiles with/without superstructure

4. CONCLUSION

According to the results, since micropile systems have significant advantages for construction in seismic areas (due to their high flexibility/ductility), and considering the settlement results of no-micropile foundations with/without superstructure that show resistance against liquefaction increases in the presence of superstructure, it can be concluded that places with less-weight (lighter) structures need more preparations against liquefaction because it incurs great damage to the structure, and micro piles are effective engineering solutions for seismic zones during this phenomenon. As the current research was aimed to show the micropile efficacy against liquefaction by reducing settlements in the presence

and absence of structures, numerical modeling was first validated with centrifuge models, the results of which were acceptably close to those of the centrifuge test. Liquefaction occurred about 4 sec up to a depth of 5 m, but at 7.5 m depth, it did not occur due to the increased effective stress caused by the upper layers of the soil. Results showed that superstructures reduced the liquefaction probability, and increasing micro piles reduced not only the settlement but also the amount of excess pore water pressure acceptably. Examining the results revealed that micro piles were more effective in reducing settlements in the absence of superstructures, concluding that in this case, dense or scattered micropile arrangements have no effects on reducing settlement, but dense arrangements help micro piles to be more effective in reducing settlement in the presence of superstructures.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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