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Analysis of Piles in Liquefied and Non-liquefied Sands due to Earthquake Vibrations Using Opensees

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Abstract. During strong earthquakes, many structures collapse due to adverse damage of substructure as the soil becomes laterally unsupported due to earthquake induced liquefaction. This paper investigates the nonlinear behavior of single piles in sands due to earthquake induced liquefaction employing three-dimensional nonlinear finite element models using Opensees. Single piles of varying thickness are tested with the ground inclined mildly. The Input ground motion was in the form of sinusoidal acceleration with a 2 Hz frequency and amplitudes ranging from 0.2 g. The data obtained from the recorders for both pile and pile-group is analyzed for displacement, bending moment and excess pore water pressure. In this series of tests, it is observed that most of the highest pile lateral loads occur at the initial stages of lateral deformation, as the excess pore pressures advances towards liquefaction. Later, the lateral loads seem to be decreased for liquefied stratum. It was found that the bending moment of piles in the liquefiable site increases significantly, compared to the non-liquefiable site, due to the loss of lateral support of the liquefied soil. Furthermore, it was found that the displacement at the base of pile in case of saturated stratum is comparatively small.

Keywords: Liquefaction, Opensees, Excess pore water pressure, Non-linear finite element.

1 Introduction

1.1 General

Pile foundations are extensively used to support high-rise buildings, bridges, ports, and offshore structures. During strong earthquakes, many structures get collapsed due to severe damage to their foundations due to extensive liquefaction. During earthquakes, in liquefied soils, pile foundation becomes laterally unsupported thereby resulting in lateral spreading of soil [1, 2]. The failure of piles in liquefiable soil is due to the buckling of pile which is due the loss of lateral support from the surrounding soil, forming a plastic hinge in the pile [3]. One of the methods to analyze piles subjected to lateral loading is beam on the nonlinear Winkler foundation (BNWF) model. It assumes the pile as beam elements and the soil as transversal and longitudinal springs. The BNWF model uses empirical p-y curves to determine the relationship between deformation and load in situations where the spring stiffness allows non-proportional load-displacements.

The results of scaled modelling experiments are used to analyze the responses of soil, piles, and superstructure by [4, 5]. In order to evaluate pile behavior in liquefiable soil, Motamed et al. [6] performed large-scale shake table test taking into account the possibility of ground liquefaction flow. The findings of Tokimatsu et al. [7] inferred the effect of kinematic and inertia forces on pile stresses from the results of large-scale shake table test conducted on piles in both dry and saturated sand. The key parameters which control the response of pile are found to be ultimate pressure from top surface layer and the ground displacement.

In recent studies, 3D finite element (FE) models are employed to investigate non-linear behavior of piles and interaction between different layers of soil with varying stiffness, piles and loads of superstructure. Cubrinovski et al. [8] performed 3D effective stress analysis to know the effect of non-liquefied crust layer on the bending moment of piles. Assimaki and Shafieezadeh [9] validated the results of physical test of liquefied soil-induced lateral spreading with that of 3D finite model results. Xu et al. [10] conducted large-shake table test having same configuration of pile in liquefied and non-liquefied soils employing multiple soil profiles in horizontal ground. The results from the test were later simulated in 3D non-linear finite element model using Opensees by Hussein and Naggar [11]. The response of single piles embedded in liquefiable and non-liquefiable sand is studied for considered input earthquake motion.

2 Methodology and modeling

2.1 Material properties

Sand is considered at two different relative densities 40 and 90%. The properties of sand used for the study are listed in Table 1. The water table at the surface and depth of 1 m are considered as liquefiable and non-liquefiable conditions respectively for the current study.

Table 1. Properties of sand layers

Parameters	Loose Sand	Dense sand
Relative density, D_r (%)	40	90
Density of soil, γ, (g/cc)	1.94	1.94
Reference pressure, p_r (kPa)	101	101
Friction angle at peak shear strength, Φ	35	37
Cohesion, C (kPa)	0.1	0.1
Void ratio, e	0.9	0.75

Two hollow steel piles of thickness 3 mm and 1.5 mm are considered for the current study. The dimensions of the model pile are adopted from Ebeido et al., [12]. These piles are classified as stiff pile and flexible pile based on bending stiffness and other properties. The properties of the piles used for the current study are presented in Table 2.

Table 2. Properties of pile and pile cap

Property	Flexible pile	Stiff pile
Material	Aluminum	Aluminum
Outer diameter (mm)	318	318
Inner diameter (mm)	315	312
Unit Weight (kN/m^3)	25.8	25.8
E (GPa)	70	70
Bending stiffness (kN-m^2)	7360	14320
Base rotational stiffness (kN-m/rad)	8500	18500
Yield bending moment (kN-m)	93	180

2.2 Modeling using Opensees

The dimensions of soil model are chosen as 11.6 × 3.5 × 5.5 m in such a way to avoid the interference of boundaries on the pile response. Fig. 1 shows the soil model containing two different sand layers in which top layer is loose sand and bottom layer is dense sand. The ground is inclined at an angle of 2° with horizontal. The modelling of elements of soil has been performed using hexahedral 8 noded isoperimetric linear elements respectively. The non-linear response of sand layer is simulated using Pressure Depend Multi Yield 02 (PDMY02) constitutive material model [13]. The pile is modeled using 3D nonlinear displacement-based beam-column elements. The water table is considered at two different levels i.e., at the surface and depth of 1 m. The input ground motion of frequency 2 Hz, duration 44 seconds and amplitude 0.2 g is applied on model piles in the form of sinusoidal acceleration.

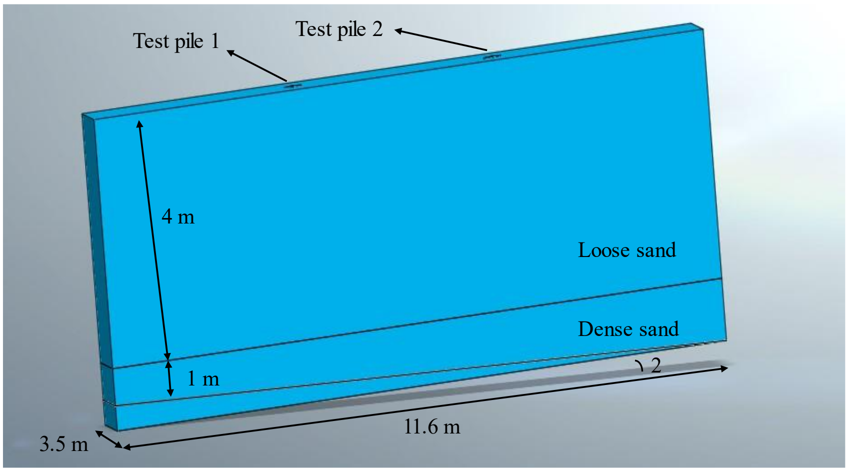


Fig. 1 Opensees model showing two different sand layers

2.3 Generating 3D mesh

The soil modeling (soil layers, pile, and loading) is followed by generation of mesh with a size of 0.5 × 0.5 × 0.5 m. Fig. 2 shows medium mesh generated for the model comprising of both flexible and stiff piles respectively. The analysis of generated model is attained in following phases. The recorders are initially defined, and the constitutive soil models are activated. A borehole is generated, and the pile is embedded in the borehole. The self-weight of the soil is added, and the model is primarily analyzed for gravity analysis. After gravity analysis, the dynamic analysis with the input ground motion is carried.

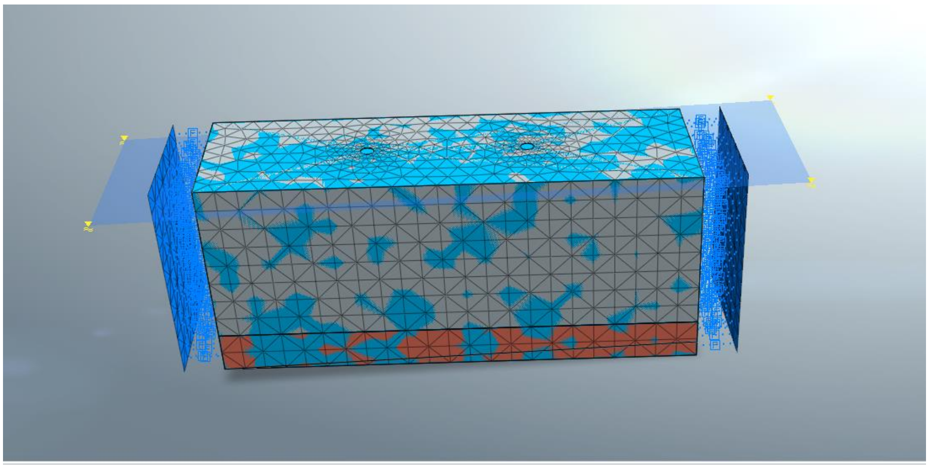


Fig. 2 Mesh generated for the model

3 Results and discussion

3.1 Validation of Opensees

The numerical modeling software Opensees is validated with experimental results of Ebeido et al., [12]. It can be inferred that the displacements obtained from numerical analysis are in agreement with the experimental displacements. The deviation of the predicted numerical deflection from that of experimental is negligible.

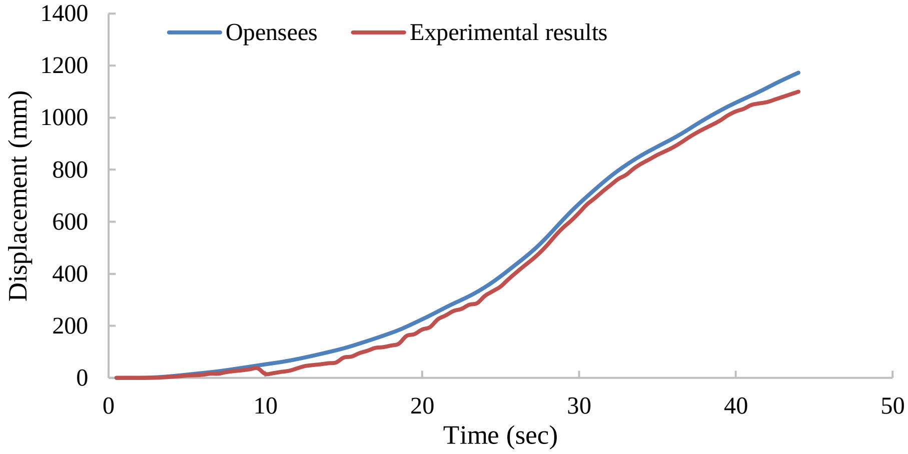


Fig. 3 Validation of Opensees software with experimental results

3.2 Response of single piles in liquefiable sand

The pile head deflection response of single pile embedded in liquefiable sand is shown in Fig. 4. It can be inferred that the deflection of stiff pile is relatively lesser than that of flexible pile. The variation in magnitude of deflection can be attributed to relatively higher resistance offered by stiff pile to the applied earthquake motion.

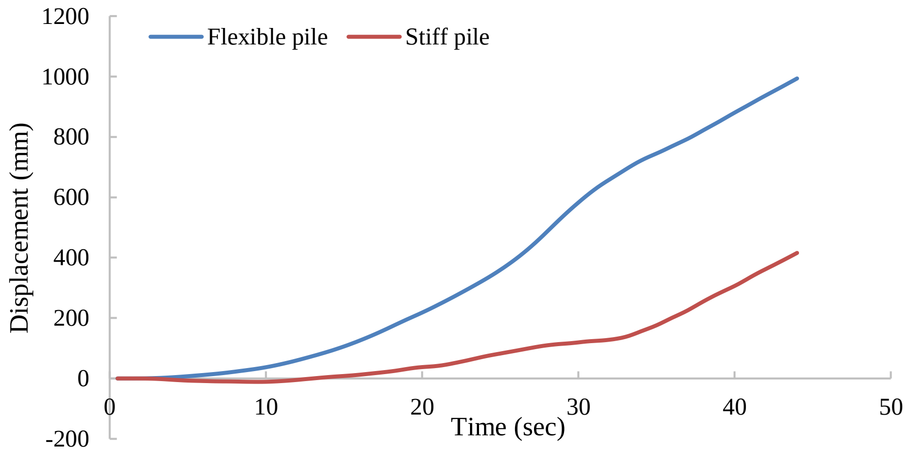
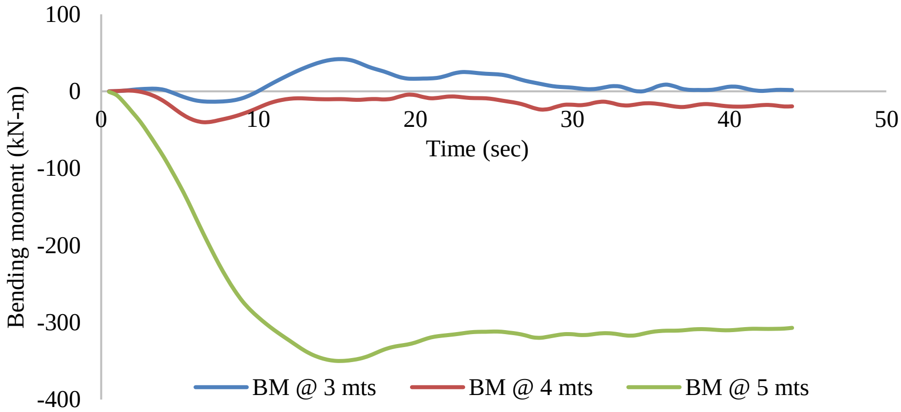
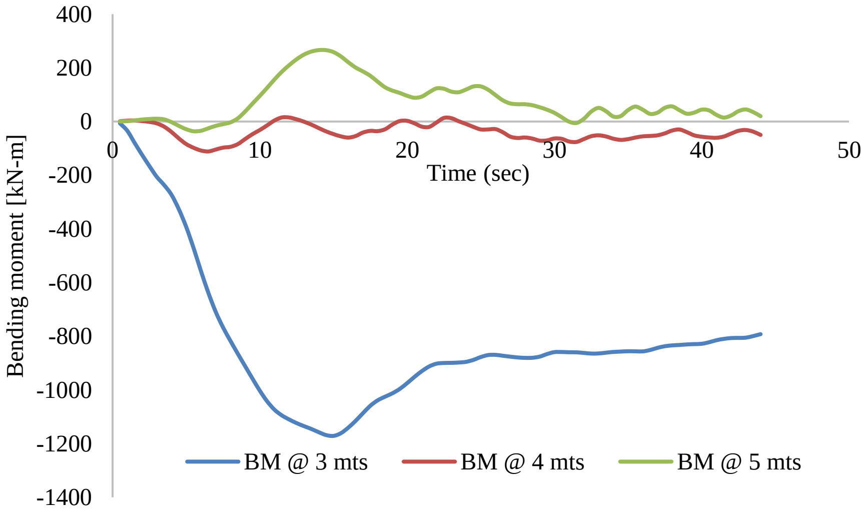


Fig. 4 Deflection response of single piles in liquefied strata

The variation of bending moments with duration for the flexible and stiff piles at depths 3, 4 and 5 m is shown in Fig. 5a and 5b. It can be inferred that maximum bending moment occurred at depth of 3 m for flexible pile. The bending moment is observed to be initially negative, increases to maximum value of 42 kN-m and then decreases. The attainment of maximum bending moment indicates the liquefaction condition [12]. It was inferred that attainment of maximum bending moment is subsequently followed by increment in pore pressure ratio, thus eventually resulting in liquefaction. However, at depth of 5 m, the negative bending moment goes on increasing due to the fixity at the soil base. The maximum bending moment of 266 kN-m occurred at depth of 5 m for stiff pile. The negative bending moment inferred to be at 3 m depth for stiff pile. The occurrence of negative bending moment at 3 m depth can be attributed to plastic state of stiff pile.



a. Variation of bending moment for flexible pile



b. Variation of bending moment for stiff pile

Fig. 5 Bending response of single piles with time in liquefied strata

3.3 Response of single piles in non-liquefiable sand

The variation of pile head deflection with time for flexible and stiff piles in non-liquefiable sand is shown in Fig. 6. It can be inferred that there is a significant variation in the deflection response of flexible pile and stiff pile. The maximum deflection of stiff pile is significantly less than that of flexible pile. These ultimate displacements on comparison with that of displacement of piles in liquefiable sand concludes that displacement of flexible pile is reduced from 1000 to 750 mm and that of stiff pile is reduced from 390 to 260 mm. This reduction in magnitude of deflection can be attributed to presence of water table at depth of 1 m relative to the surface, thus leading to improved resistance to earthquake loading.

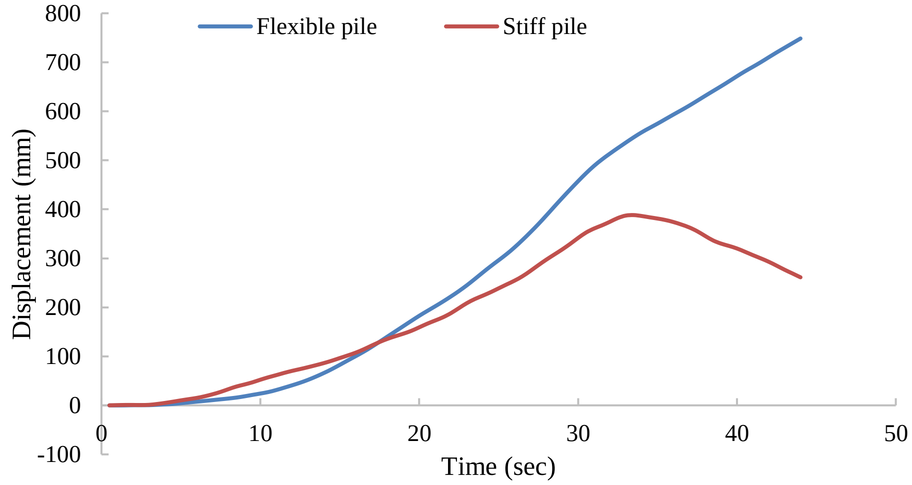
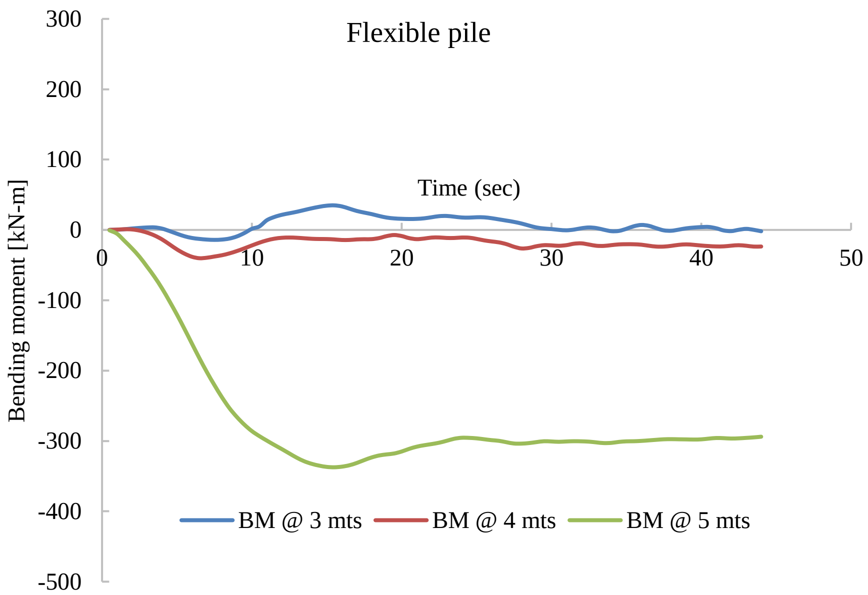
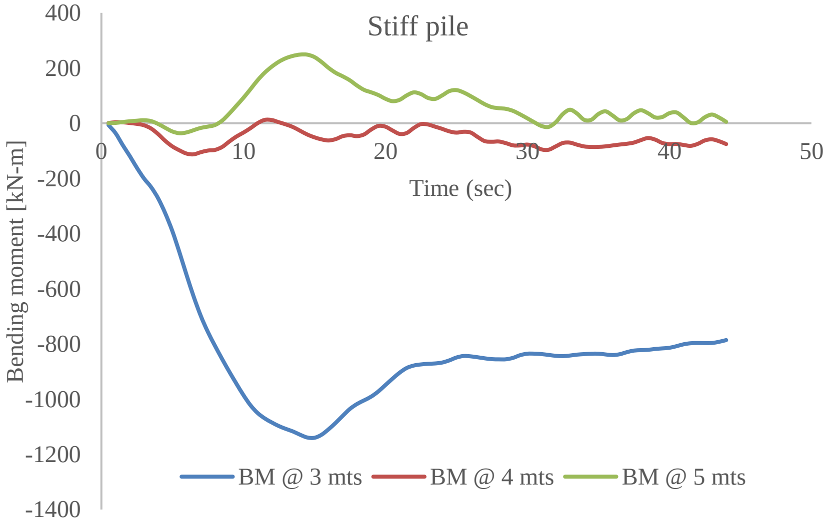


Fig. 6. Deflection response of single piles in non-liquefied sand

The bending moment response of piles in non-liquefiable sand is presented in Fig. 7a and 7b. The response profiles are similar to that of piles in liquefiable strata with negative bending moment occurring at depths of 5 and 3 m for flexible and stiff piles respectively. The response profiles of maximum bending moments coincide with depths of 3 and 5 m for flexible and stiff piles respectively. The magnitude of maximum bending moment in non-liquefiable sand decreased to 35 from 42 kN-m and 248 from 266 kN-m for flexible and stiff piles respectively. The decrease in bending moment is due to associated lateral pressure from the stratum.



a. Variation of bending moment for flexible pile



b. Variation of bending moment for stiff pile

Fig. 7. Bending response of piles in non-liquefiable sand

4 Conclusions

The response of single piles embedded in stratified soil of varying water table depths is analyzed under the application of earthquake motion. The following conclusions can be drawn from the study:

- The presence of dense layer decreases peak acceleration and conversely time required for liquefaction is increased.
- The displacement at the end of shaking is less than maximum displacement if the soil is confined.
- The displacements of pile heads are reduced due to densification of bottom layer.
- In stiff pile, the point of contra flexure shifts from bottom of pile to a point above the interface of the two layers.

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