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Behavior of Single Pile embedded in Multi-layered soil subjected to Dynamic Excitation

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Abstract. The study of the response of pile foundation under earthquake loading has been quite complex in the past due to the inability of incorporation of actual geotechnical aspects during seismic analysis. With recent advances in the field of civil engineering, some softwares have been created which can be used to incorporate the geotechnical aspects. The user interface of OpenSees, OpenSees PL has the ability to reproduce SSI effects due to earthquake loading computationally and thus can be used to conduct FE computations to obtain realistic results of seismic analyses. In this research work, single circular fixed-head concrete piles of 0.4m and 0.8m diameters embedded in multilayered soil with rigid bed rock base are taken into consideration. For the soil-pile model, 8-noded brick elements are used to model the soil and beam-column elements to model the pile and rigid beam-column elements to represent the pile cross-sectional diameter and the interface with surrounding 3D soil elements. The same elements have been used by Lu et al. (2011) to model the pile-soil system, who validated the use of OpenSees PL for seismic analysis of pile foundation with analytical results by Abedzedah et al. (2004). The dynamic analysis is conducted by applying sinusoidal excitations having peak ground acceleration of 0.3g of frequency 2 Hz at the base. The response of each pile embedded in different soil combination is obtained in terms of pile displacement and maximum bending moment experienced by pile. It is seen that the maximum magnitude of bending moment of pile due to dynamic analysis is similar to that obtained from pushover analysis of pile, thus verifying the accuracy of the results obtained from dynamic analysis.

Keywords: OpenSees PL, Dynamic analysis, Pushover analysis.

1 Introduction

1.1 Response of pile foundation due to earthquake

Past earthquake case histories show that structures supported by different types of foundations, is affected in a different manner depending upon the type of earthquake and the type of foundation. The failure patterns of piles have been seen to be different for each case depending on the peak ground acceleration, geometric configuration of pile foundation and surrounding soil layers. Pile foundations consisting of concrete piles were seen to crack at pile head and at different depths after the Kobe earthquake in 1995, which had different peak ground acceleration in different routes [2]. Also, excessive lateral ground movement resulted in very large kinematic load on the piles which further lead to collapse of the piles. The Niigata earthquake in 1964 resulted in collapse of many bridges due to lateral spreading of the soil caused by liquefaction, which resulted in cracks not only at the top of the foundation, but also at the bottom [3]. Since the reason of failure of pile may be different in different cases, it is important to study the behavior of pile embedded in soil. However, prediction of the dynamic response of foundation-ground system is quite challenging due to complexity of soil-foundation interface mechanisms. Lack of advanced nonlinear soil behaviour tools along with difficulty in soil-structure interaction modeling also lead to inaccurate prediction of response of pile. Since soil-structure interaction (SSI) during an earthquake has shown great impact on the seismic response of structure, it is mandatory to incorporate the SSI during analysis for better assessment of the performance of the structure. From various investigations conducted on liquefying soil, it was stated that progressive build-up of pore water pressure result in loss of strength and stiffness which result in large bending moments and shear force on pile [4]. Thus it is extremely important to conduct proper seismic analysis for foundations surrounded by liquefiable as well as non liquefiable soil to obtain reliable results for design of such foundations. The objective of this paper is to study the influence of multilayered soil on pile in terms of pile head displacement and maximum bending moment on pile due to dynamic seismic analysis.

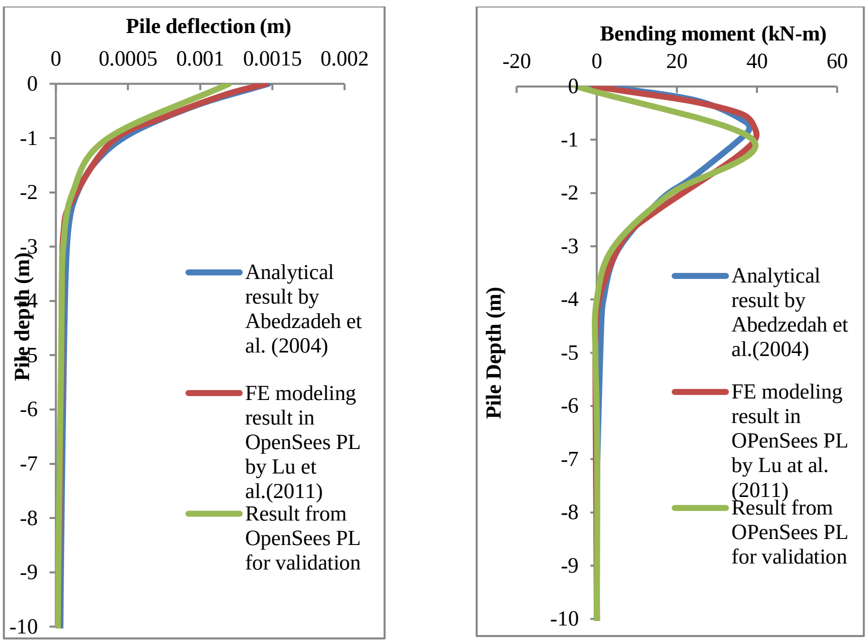
1.2 Finite Element Analysis using OpenSees PL

Earthquake engineering simulations are performed using Finite Element Analysis program which can incorporate element formulation, material relations, analysis algorithms and solution strategies. Finite Element Analysis software utilizes object-oriented design principles and programming approach which has brought revolution in the way software is written. One such software framework was created by Pacific Earthquake Engineering Research (PEER) Center for developing applications that could be used to simulate the performance of structural and geotechnical systems subjected to seismic loading. This framework was named as OpenSees (Open System for Earthquake Engineering Simulation). The main feature of OpenSees is that it is a finite element code for non linear static as well as dynamic structural analyses that was developed under the paradigm of object-oriented programming. OpenSees allows usage of object oriented programming language C++, as well as Tcl (Tool Command Language), which is a pre-Java scripting language.

Using the pre- and post- processing efforts of OpenSees, a user-friendly interface known as OpenSees PL was created for 3D foundation-ground analyses such that the complicated soil-structure interaction mechanism could be incorporated while analyzing the foundation under seismic loading in order to represent the actual geometric configuration that is involved due to soil-structure interaction. OpenSees PL is a FE graphical user-interface for 3D ground-structure interaction response which allows conducting pushover analysis as well as seismic simulations [6].

1.3 Validation of seismic analysis using OpenSees PL

To validate the use of OpenSees PL for obtaining desired results of seismic analysis of pile foundation, pile-soil configuration of single pile embedded in soil is modeled as per Lu et al. (2011). Lu et al. (2011) validated the use of OpenSees PL by verifying with analytical results obtained by Abedzedah et al. (2004). As per the modeling by Lu et al. (2011), a circular free-head pile of 10.15m length and radius 203.20mm, fully embedded in a 20.12m soil domain of submerged unit weight 9.87 kN/m^3 is modeled in OpenSees PL. The pile is modeled using linear beam-column elements so that bending moment, axial loads and shear force could be viewed easily with rigid beam-column elements representing the diameter and interface with the surrounding soil elements. The soil is modeled using 8-node brick elements with *MultiYield* material to capture seismic events accurately. Lateral incremental pushover loading is applied monotonically at the pile head up to a total load of 140.12 kN. Fig.1. shows the pile deflection and the bending moment experienced by the pile throughout its length due to pushover loading. From the results, it is seen that pile response in terms of deflection and bending moment obtained from pushover analysis in OpenSees PL is similar to the analytical results of pushover analysis obtained by Abedzedah et al.(2004). Thus, for conducting seismic analysis of pile foundation in OpenSees PL for this research work, pile-soil system is modeled as per Lu et al. (2011).



(a) (b)

Fig.1. Comparison of analytical results and FE modeling results in terms of (a) Pile deflection and (b) bending moment of pile for seismic analysis of pile-soil system for validation

2 Seismic Analysis of Pile Foundation

Dynamic analysis and pushover analysis is conducted on pile-soil system using OpenSees PL. A 0.4m and 0.8m diameter fixed pile is considered to be embedded in soil consisting of different layers of soil. Combination of cohesionless soil and cohesive soil is considered to be placed at different positions to study the impact of the surrounding soil on the pile subjected to seismic loading.

2.1 Numerical modeling of pile-soil system

Similar pile and soil elements used by Lu et al. (2011) have been used for modeling the pile-soil system for this research work. The 10m long circular pile is modeled using linear beam-column elements. Rigid beam-column elements, which are 10^4 times stiffer than the pile elements axially and flexurally, are used for representing the cross-sectional diameter and the interface with the soil elements surrounding the pile. The pile is considered to be fixed at the top and bottom with water table up to the pile head. The mass density of the considered pile is taken as 2400 kg/m^3. The Young's modulus and the shear modulus are $3x10^7$ kPa and $1.154x10^7$ kPa respectively. For 0.4m diameter pile, the moment inertia of the pile and torsion constant is 0.00125 m^4 and 0.00251 m^4 respectively. For 0.8m diameter pile, the moment inertia of the pile and torsion constant is 0.02010 m^4 and 0.040212 m^4 respectively.

The 10m soil domain consists of layers cohesionless very loose sand and cohesive medium soil in three different combinations. The non linear soil modeling is done by modeling the soil domain with 8-node brick elements using *MultiYield* material. Sand is modeled using *PressureDependMultiYield* soil model and cohesive medium soil is modeled using *PressureIndependMultiYield* model. The details about the soil elastic properties, soil nonlinear properties, fluid properties, dilatancy properties and liquefaction properties for the saturated cohesionless soil and cohesive soil are given in Table 1. The water table is considered up to the pile head so as to consider liquefaction analysis while conducting dynamic or static analyses. The soil combinations are:

1. Cohesive medium soil (5m) + Cohesionless very loose sand (5m)
2. Cohesionless very loose sand (5m) + Cohesive medium soil (5m)
3. Cohesive medium soil (2m) + Cohesionless very loose sand (6m) + Cohesive medium soil (2m)

The boundary condition is rigid box type and is considered to be fixed at the bottom in all directions. The plane of symmetry for half mesh configuration is fixed in Y direction while keeping it free in Z and X direction to model 3D full mesh scenario.

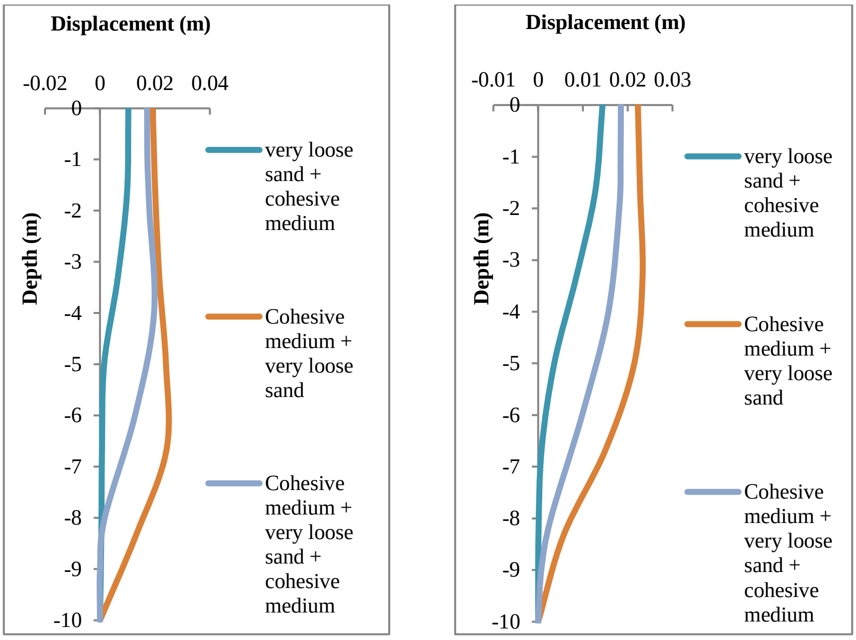
2.2 Dynamic analysis results of single pile

Dynamic analysis of single pile embedded in each type of soil combination is conducted by applying dynamic excitation in the form of sinusoidal wave of 0.3g peak ground acceleration having frequency of 2 Hz for 10 cycles at the base of the pile. Fig.2. shows the displacement profiles of 0.4m and 0.8m diameter piles due to dynamic analysis. Pile surrounded by cohesive medium soil layer placed above cohesionless very loose sand layer results in high displacement throughout the pile length. Maximum displacement of 0.0242m is experienced by the pile at the beginning of the sand layer. The displacement of pile at the pile head is 0.0192m. Interchanging of soil layers result in high pile displacement of 0.0103m at the pile head where cohesionless very loose sand is present. For cohesionless very loose sand sandwiched between cohesive medium soil layers, 0.0196m displacement is experienced by the pile at the beginning of the sand layer. The displacement at the pile head is 0.0171m which is surrounded by cohesive medium soil layer. However, for the same pile surrounded by cohesive medium soil layer at the bottom of the pile, witnesses negligible displacement. 0.8m diameter pile is seen to witness the highest pile displacement at the pile head for all the soil combinations irrespective of the location of cohesionless very loose sand layer. Pile surrounded by cohesive medium soil placed above cohesionless very loose sand displaces the pile head by 0.0182m, which is the maximum displacement witnessed by the pile. Interchanging of soil layer position reduces the pile head displacement to 0.0143m. For this soil combination, pile witnesses negligible displacement beyond 6m depth at the cohesive medium soil layer. Pile surrounded by cohesionless very loose sand sandwiched between cohesive medium soil layers result in pile head displacement of 0.0180m.

Table 1. Soil Properties of cohesionless very loose sand and cohesive medium soil

	Cohesionless very loose sand	Cohesive medium soil
Soil Elastic properties		
Saturated mass density (Mg/m3)	1.7	1.5
Reference pressure (kPa)	80	100
Reference Shear modulus (kPa)	55000	60000
Reference Bulk modulus (kPa)	150000	300000
Soil Nonlinear Properties		
Friction (deg)	29	0
Cohesion(c) multiplied by((sqrt(3))/2)	0.2	37
Fluid Properties		
Fluid mass density (Mg/m3)	1	1
Horizontal permeability (m/s)	6.6E-05	1.00E-0.9
Vertical permeability (m/s)	6.6E-05	1.00E-0.9
Dilatancy/liquefaction Properties		-
Phase transformation angle (deg)	29	-
Contraction parameter	0.21	-
Dilation parameter 1	0	-
Dilation parameter 2	0	-
Liquefaction parameter 1	10	-
Liquefaction parameter 2	0.02	-
Liquefaction parameter 3	1	-

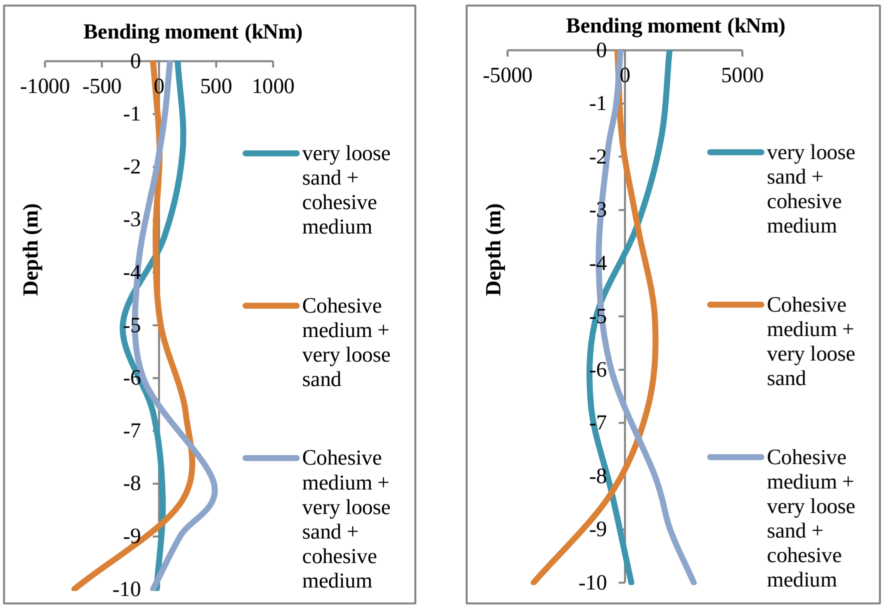
Fig. 3. shows the bending moments experienced by 0.4m and 0.8m diameter pile due to dynamic analysis. From the graphs it can be seen that 0.4m diameter pile witnesses change in bending behaviour at more locations than 0.8m diameter pile. For 0.4m diameter pile, cohesive soil placed above cohesionless very loose sand layer results in the maximum magnitude of bending moment 742.39 kN-m. On interchanging the soil layers, the maximum magnitude of bending moment experienced by pile reduces to 317.72kN-m. This shows the influence of positioning of soil layers on response of pile. For cohesionless very loose sand sandwiched between cohesive soil layers, the maximum bending moment acting on pile is 481.53kN-m. Similar influence of positioning of soil layers is seen to occur for 0.8m diameter pile as well. The maximum magnitude of bending moment experienced by pile surrounded by cohesive medium soil placed above cohesionless very loose sand is 4291.9kN-m. For pile surrounded by cohesionless very loose sand layer placed above cohesive medium soil layer, the maximum bending moment experienced by pile is 1897.81kN-m. Sandwiching cohesionless very loose sand between cohesive medium soil result in maximum bending moment of magnitude 3334.06 kN-m.



(a) (b)

Fig.2. Displacement results of (a) 0.4m and (b) 0.8m diameter pile subjected to dynamic analysis with PGA 0.3g

From the dynamic analysis results of 0.4m and 0.8m diameter pile, it is seen that the type of surrounding soil present along with the positioning of soil layers affect the response of piles. Lower diameter piles are seen to be affected more than higher diameter piles. Different position of soil layers result in different pile displacements for 0.4m diameter pile throughout its length. Presence of cohesionless very loose sand at any layer results in higher displacement of pile within that layer. However, 0.8m diameter pile witness high pile displacement at the pile head for all soil combinations even though there is difference amongst the displacement values for each soil combination. The magnitude of maximum bending moment is seen to depend on the positioning of soil layers and the type of soil present for both the diameters of pile. Presence of cohesionless very loose sand at the top layer results in low magnitude of maximum bending moment witnessed by the pile.



(a) (b)

Fig.3. Bending Moment results of (a) 0.4m and (b) diameter pile subjected to dynamic analysis with PGA 0.3g

2.3 Pushover analysis results of single pile

Further, pushover analysis of the same piles embedded in the same soil conditions is conducted. The pile is pushed by applying incremental monotonic horizontal loading at the pile head. The load is applied until the pile head displacement is same as that obtained from dynamic analysis. Table 2 shows the magnitudes of maximum bending moment witnessed by piles due to pushover analysis.

Table 2. Maximum magnitude of bending moment due to pushover analysis

Soil combination	0.4m diameter pile	0.8m diameter pile
Cohesive medium soil + Cohesionless very Loose sand	861.5 kN-m	4798 kN-m
Cohesionless very loose sand + Cohesive medium soil	302.4 kN-m	1964 kN-m
Cohesive medium soil + Cohesionless very loose sand + Cohesive medium soil	561.5 kN-m	3564 kN-m

2.4 Comparison of dynamic analysis and pushover analysis results

As per Fig.4., the magnitude of maximum bending moment witnessed by each pile is comparable for both the analyses for all the soil combinations. Of the three soil combinations considered, cohesive medium soil layer placed above cohesionless very loose sand results in the highest magnitude of maximum bending moment for both the analyses. For this soil combination, 0.4m diameter pile witnesses 742.68 kN-m and 861.5 kN-m for dynamic and pushover analyses respectively. 0.8m diameter pile witnesses maximum bending moment of magnitudes 4291.9 kN-m and 4798 kN-m for dynamic and pushover analyses respectively. Interchanging position of soil layers result is lower magnitudes of maximum bending moment. 0.4m diameter pile witnesses 208.01 kN-m and 302.4 kN-m for dynamic and pushover analyses. For this soil combination, 0.8m diameter pile results in maximum bending moment of magnitudes 1897.81 kN-m and 1964 kN-m for dynamic and pushover analyses. However, the triple layered soil combination containing cohesionless very loose sand sandwiched between cohesive medium soil layers, result in maximum bending moments of magnitude 481.53 kN-m and 561.5 kN-m for dynamic and pushover analyses for 0.4m diameter pile. For 0.8m diameter pile, the maximum bending moment for this soil combination is 3334.06 kN-m and 3564 kN-m for dynamic and pushover analyses.

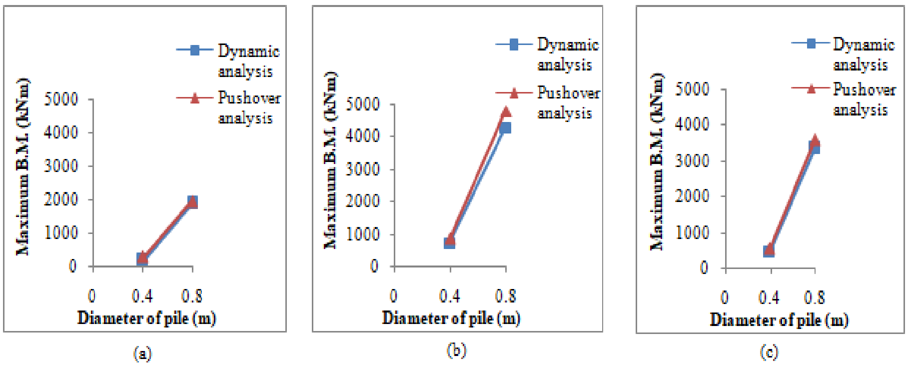


Fig.4. Magnitudes of maximum bending moment of piles surrounded by (a) Cohesionless very loose sand + Cohesive medium soil (b) Cohesive medium soil + Cohesionless very loose sand (c) Cohesive medium soil + Cohesionless very loose sand + Cohesive medium soil

3 Conclusions

From the seismic analysis conducted on piles of different diameter each surrounded by different soil combinations, it can be concluded that:

1. The type of soil surrounding pile, along with the positioning of soil layer in different layered soil combinations, influence the behaviour of pile subjected to seismic loading.
2. Lower diameter piles are affected more than higher diameter piles due to different surrounding soil conditions.
3. On conducting pushover analysis up to the pile head displacement obtained from dynamic analysis, comparable results of maximum bending moment magnitudes are achieved for both the analyses, thus confirming the results of pile behaviour obtained from dynamic analysis due to various surrounding soil conditions.

References

1. Abedzadeh F., and Pak R. Y. S.: Continuum Mechanics of Lateral Soil-Pile Interaction, Journal of Engineering Mechanics, 130(11), 1309-1318. (2004).
2. Amiri, S.K.: The earthquake response of bridge pile foundations to liquefaction induced lateral spread displacement demands, Phd Thesis, University of South California, Los Angeles (2008).
3. Bhattacharya, S. and Madabhushi, S. P. G.: A critical review of methods for pile design in seismically liquefiable soils. Bull Earthquake Eng (2008) 6:407–446. DOI 10.1007/s10518-008-9068-3,Springer (2008).
4. Inqualabi, K.Q., Garg, R.K. and Rao, K.B.: Seismic Vulnerability of Urban Bridges Due to Liquefaction Using Nonlinear Pushover Analysis and Assessing Parameters For Damage Detection. *11th International Symposium on Plasticity and Impact Mechanics, IMPLAST 2016*. Elsevier. Procedia Engineering 173 (2017) 1739 – 1746, New Delhi (2016).
5. Lu J, Elgamal A. and Yang Z.: OpenSees PL: 3D Lateral Pile-Ground Interaction. User Manual. University of California, San Diego, (2011).
6. Wang, N.: Three-Dimensional Modeling of Ground-Pile Systems and Bridge Foundations. Phd Thesis. University of California, San Diego, (2015).