Comparison of Response of Pushover Analysis and Dynamic Analysis of Pile Foundation

Bidisha Borthakur and Arup Bhattacharjee

Abstract Pile foundations are the most vulnerable components of the entire structure and are prone to failure due to earthquake loading. Thus it is mandatory for proper seismic analyses to be conducted with the incorporation of all the necessary influencing factors to ensure no failure occurs to the pile foundation. Even though dynamic analysis has been the conventional seismic analysis method, a new nonlinear static analysis known as pushover analysis is seen to realistically predict earthquake response of the pile. This calls for proper research to be conducted to check if static pushover analysis can be used as an alternative to dynamic analysis for seismic analysis of structures to save time and ease on the complexity of dynamic analysis. In this research work, single piles of different diameter have been taken into consideration which has been embedded in stratified soil containing layers of different soil types. Dynamic analysis and static pushover analysis have been conducted for each case to compare the results of both the analyses. The Finite Element modeling as well as the analyses has been conducted in the user friendly interface of OpenSees known as OpenSees PL. From the results obtained, it is seen that pushover analysis can estimate the maximum bending moment witnessed by the pile while taking into account the effects of surrounding soil condition on it due to earthquake loading. Similar results of maximum bending moment have been obtained for both the analyses.s

Keywords Pushover analysis · Dynamic analysis · OpenSees PL

1 Introduction

1.1 General

Pile foundations have always been a solution to civil engineers when load has to be transferred from the superstructure through weaker soil strata onto less compressible soil or rock. However from various seismic investigations, it has been found that piles are the most vulnerable components of the entire structure and failure of pile has

B. Borthakur (✉) · A. Bhattacharjee
Department of Civil Engineering, Jorhat Engineering College, Jorhat, Assam, India

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been seen to result in the failure of the entire structure. The main reason behind this could be the unaccountability of surrounding soil condition while designing the pile foundation. In earthquake prone areas, the surrounding soil result in a combination of vertical and horizontal forces acting on the pile in addition to the load from the superstructure. Thus pile foundation should be designed by taking all the necessary factors into consideration such that no failure of foundation occurs due to seismic loading and proper seismic analyses should be conducted to do so. The dynamic analysis has been the conventional seismic analysis method for obtaining response of a structure due to earthquake loading. However, in recent times it has been seen that static nonlinear pushover analysis can be used in seismic design because of its ability to simulate equivalent peak load that occurs on the structure during earthquake. The ability of pushover analysis to simulate the peak dynamic response of structure decides the accuracy of this method [5]. The pushover analysis helps to improve understanding of post-yield structural behavior and results in more accurate prediction of global displacement along with realistic prediction of earthquake demand in individual structural elements [2]. It can also approximately take into account the redistribution of internal forces occurring in the structure due to inertia force which cannot be resisted within elastic range of the structure, thus helping to predict the seismic forces acting on the structure when seismic load is applied, which can further help in controlling the performance of the structure when subjected to earthquake [3].

Since pushover analysis can accurately simulate the dynamic response of a structure in spite of being a static analysis, its use as an alternative to dynamic analysis should be checked in order to make seismic analyses less complex and less time consuming. In this research work, single piles of different diameter embedded in different stratified soil conditions have been taken into consideration. Dynamic analysis as well as static pushover analysis has been conducted for each case to check the accuracy of response of pile due to pushover analysis with dynamic analysis.

1.2 3D Ground-Foundation Analyses Using OpenSees PL

A user-friendly interface of OpenSees, known as OpenSees PL was created using the using the pre- and post- processing efforts of OpenSees. 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. It is a FE graphical user-interface for 3D ground-structure interaction response which allows conducting pushover analysis as well as seismic simulations [7]. This Finite Element Analysis software utilizes object-oriented design principles and programming approach and can incorporate element formulation, material relations, analysis algorithms and solution strategies.

1.3 Validation of Seismic Analysis Using OpenSees PL

The seismic analysis of pile foundation using OpenSees PL is validated with the results obtained by Lu et al. [4] and analytical results obtained by Abedzedah et al. [1]. A circular free-head pile of 10.15 m length and radius 203.20 mm, fully embedded in a 20.12 m soil domain of submerged unit weight 9.87 kN/m^3 is modeled in OpenSees PL [4]. 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. Figure 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 [1]. Thus for the seismic analysis of pile foundation in OpenSees PL for this study, modeling is done as per [4].

2 Seismic Analyses of Pile Embedded in Stratified Soil

Single piles of diameters 0.4 m and 0.8 m are considered to be fully embedded in stratified soil containing different layers of cohesive soil and cohesionless soil.

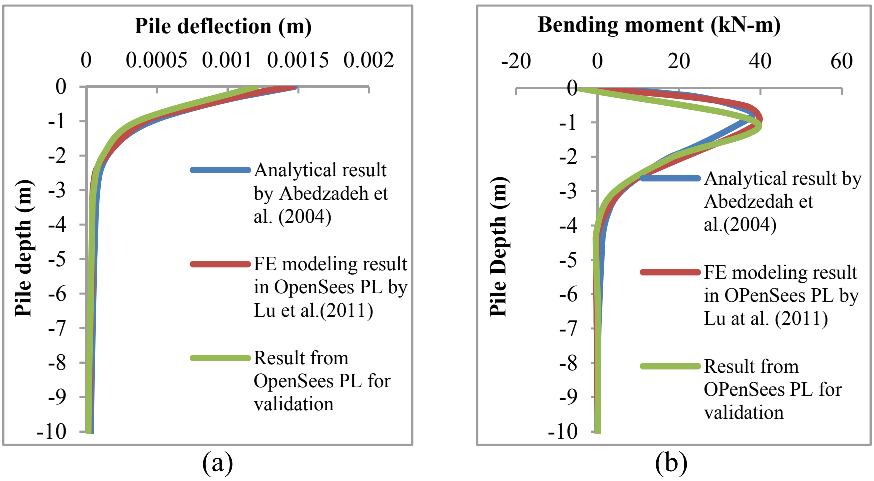

Fig. 1 Comparison of analytical results and FE modeling results in terms of (**a**) Pile deflection and (**b**) bending moment of pile for seismic analysis of pile-soil system for validation

Dynamic analysis as well as pushover analysis is conducted on each pile for each case of surrounding soil condition to compare to response of pile for both the analyses.

2.1 Numerical Modeling of Pile-Soil System in Opensees PL

The numerical modeling of pile is done in OpenSees PL according to [4]. To demonstrate the influence of non linear soil response, [7] considered a cohesion of 40.68 kPa in addition to the elastic properties specified by [4]. The fixed head circular piles of diameter are considered to be fully embedded in a 10 m soil domain consisting of various combinations of layers of soil. The pile is modeled using beam-column elements and rigid beam-column elements are used to represent the cross-sectional diameter and the interface with the soil elements surrounding the pile. The water table is considered to be up to the ground surface. The mass densities of the piles are taken as 2400 kg/m^3. The Young's modulus and the shear modulus are 3×10^7 kPa and 1.154×10^7 kPa respectively. For 0.4 m diameter pile, the moment inertia of the pile and torsion constant is 0.00125 m^4 and 0.00251 m^4 respectively. For 0.8 m diameter pile, the moment inertia of the pile and torsion constant is 0.02010 m^4 and 0.040212 m^4 respectively.

The modeling of the non linear soil domain is done using 8-node brick elements. Cohesionless soil is modeled using *PressureDependMultiYield* soil model and cohesive soil is modeled using *PressureIndependMultiYield* model. The water table is considered up to the pile head so as to consider liquefaction analysis while conducting dynamic or pushover analyses. 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. 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.

Wang [7] demonstrate the influence of non linear soil response in addition to the elastic response specified by [4]. On this pile-soil system, pushover analysis was conducted by Wang [7] by applying a total load of 420.36 kN incrementally at the pile head. Figure 2 shows the comparison of pushover curve for a typical case of single pile embedded in single layered soil as obtained by Wang [7] and in present analyses. It is seen from the results that the pushover analysis curve is comparable to that obtained by Wang [7] for both soil cases.

Table 1 Soil Properties of cohesionless and cohesive soil

	Cohesionless very loose sand	Cohesionless Dense sand	Cohesive medium soil	Cohesive stiff soil
Soil elastic properties				
Saturated mass density (Mg/m^3)	1.7	2.1	1.5	1.8
Reference pressure (kPa)	80	80	100	100
Reference Shear modulus (kPa)	55,000	130,000	60,000	150,000
Reference Bulk modulus (kPa)	150,000	390,000	300,000	750,000
Soil nonlinear properties				
Friction (deg)	29	40	0	0
Cohesion (kPa)	0.2	0.3	37	75
Fluid properties				
Fluid mass density (Mg/m^3)	1	1	1	1
Horizontal permeability (m/s)	6.6E-05	6.6E-05	1.00E-0.9	1.00E-0.9
Vertical permeability (m/s)	6.6E-05	6.6E-05	1.00E-0.9	1.00E-0.9
Dilatancy/liquefaction properties				
Phase transformation angle (deg)	29	27	–	–
Contraction parameter	0.21	0.03	–	–
Dilation parameter 1	0	0.8	–	–
Dilation parameter 2	0	5	–	–
Liquefaction parameter 1	10	0	–	–
Liquefaction parameter 2	0.02	0	–	–
Liquefaction parameter 3	1	0	–	–

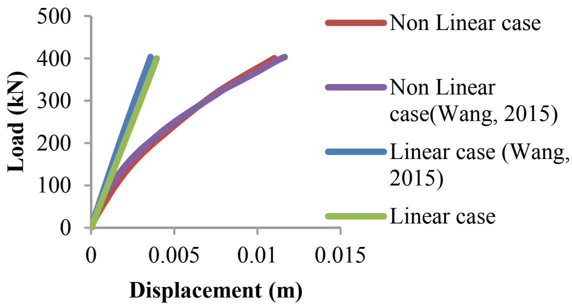

Fig. 2 Pushover analysis curves for typical case of single pile embedded in single layered soil

2.2 Numerical Modeling of Piles Embedded in Multi-Layered Soil

Using the validated model properties, the fixed head piles of different diameters embedded in various combinations of soil layers are considered for dynamic as well as pushover analysis. The soil domain of 10 m depth consist of two or three layers of different cohesive and cohesionless soil types considered in the present analysis is shown in Table 2 and Fig. 3.

2.3 Dynamic Analysis Results of Single Pile Embedded in Stratified Soil

In order to apply an earthquake of magnitude 7.0 in Richter scale [6], dynamic excitation in the form of sinusoidal wave of 0.3 g peak ground acceleration having frequency of 2 Hz is applied for 10 cycles at the base of the pile. Table 3 shows the maximum pile head displacement for each case of surrounding soil conditions obtained from dynamic analysis. The pile head displacement is seen to be high for soil containing layers of cohesionless very loose sand at any location.

Figure 4 shows the bending moment profiles of 0.4 m and 0.8 m diameter piles surrounded by double layered and triple layered soils. From the graphs, it is seen that presence of cohesionless very loose sand in any layer results in higher magnitude of bending moment witnessed by the piles for both 0.4 m and 0.8 m diameter piles. However, cohesionless dense soil in any layer is seen to result in lower magnitude of bending moment witnessed by the piles.

For 0.4 m diameter pile surrounded by cohesionless dense sand placed above cohesive medium soil, maximum magnitude of bending moment witnessed by pile is 176.42 kN-m. By interchanging the positions of layers i.e. cohesive medium soil placed above cohesionless dense sand, the maximum bending moment reduces to 87.01 kN-m. By replacing cohesionless dense sand layer with cohesionless very loose sand, the magnitude of maximum bending moment is 208.01 kN-m for sand

Table 2 Soil combinations of double and triple layered soil profile

Combination	Layer	Soil	Depth
Double layered soil			
1	Layer 1	Cohesionless dense sand	5 m
	Layer 2	Cohesive medium soil	5 m
2	Layer 1	Cohesive medium soil	5 m
	Layer 2	Cohesionless dense sand	5 m
3	Layer 1	Cohesionless very loose sand	5 m
	Layer 2	Cohesive medium soil	5 m
4	Layer 1	Cohesive medium soil	5 m
	Layer 2	Cohesionless very loose sand	5 m
Triple layered soil			
5	Layer 1	Cohesive medium soil	2 m
	Layer 2	Cohesionless dense sand	6 m
	Layer 3	Cohesive medium soil	2 m
6	Layer 1	Cohesive stiff soil	2 m
	Layer 2	Cohesionless dense sand	6 m
	Layer 3	Cohesive stiff soil	2 m
7	Layer 1	Cohesive medium soil	2 m
	Layer 2	Cohesionless very loose sand	6 m
	Layer 3	Cohesive medium soil	2 m
8	Layer 1	Cohesive stiff soil	2 m
	Layer 2	Cohesionless very loose sand	6 m
	Layer 3	Cohesive stiff soil	2 m

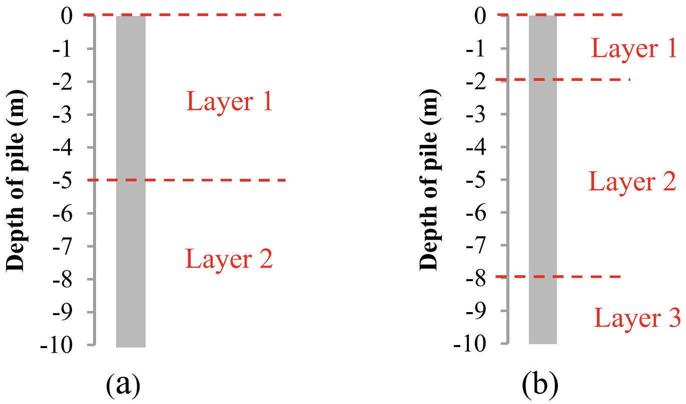

Fig. 3 Pile embedded in soil consisting of (**a**) double layered soil (**b**) triple layered soil

Table 3 Pile head displacements of piles surrounded by different soil combinations

Soil combination	0.4 m diameter	0.8 m diameter
Double layered soil		
Cohesionless dense sand + Cohesive medium soil	0.004999 m	0.005275 m
Cohesive medium soil + Cohesionless dense sand	0.001243 m	0.001197 m
Cohesionless very loose sand + Cohesive medium soil	0.01033 m	0.01437 m
Cohesive medium soil + Cohesionless very loose sand	0.0222 m	0.01827 m
Triple layered soil		
Cohesive medium soil + Cohesionless dense sand + Cohesive medium soil	0.003225 m	0.002436 m
Cohesive stiff soil + Cohesionless dense sand + Cohesive stiff soil	0.0006194 m	0.0006046 m
Cohesive medium soil + Cohesionless very loose sand + Cohesive medium	0.01915 m	0.01807 m
Cohesive stiff soil + Cohesionless very loose sand + Cohesive stiff	0.005404 m	0.009867 m

layer placed above cohesive medium soil layer. On interchanging the positions of soil layers, the magnitude of maximum bending moment increase to 742.39 kN-m. For triple layered soil containing cohesionless dense sand sandwiched between cohesive medium soil layers, the maximum magnitude of bending moment is 218.36 kN-m. By replacing cohesive medium soil layers with cohesive stiff soil, the magnitude of maximum bending moment reduces to 61.05 kN-m. For cohesionless very loose sand sandwiched between cohesive medium soil layers, the magnitude of maximum bending moment is the highest with magnitude 481.53 kN-m. However, on replacing cohesive medium soil layers with cohesive stiff soil, the maximum bending moment reduces to 394.92 kN-m.

For 0.8 m diameter piles, pile surrounded by cohesionless dense sand placed above cohesive medium soil layer, the maximum bending moment of magnitude is 992.65 kN-m. By interchanging the position of soil layers, the bending moment reduces to 809.65 kN-m. For cohesionless very loose sand placed above cohesive medium soil, the magnitude of maximum bending moment is 1897.81 kN-m. By interchanging position of soil layers, the bending moment is 3891.9 kN-m. Further, for triple layered soil, the maximum magnitude of bending moment of pile surrounded by cohesionless dense sand sandwiched between cohesive medium soil layers is 1127.7 kN-m. By replacing cohesive medium soil layers with cohesive stiff soil results in lower magnitude of maximum bending moment of 408.08 kN-m. For 0.8 m diameter pile surrounded by cohesionless very loose sand sandwiched between cohesive medium soil layer, the maximum magnitude of bending moment is 2934.02 kN-m. By replacing cohesive medium soil layer with cohesive stiff soil, the magnitude of maximum bending moment on pile is 2998.6 kN-m.

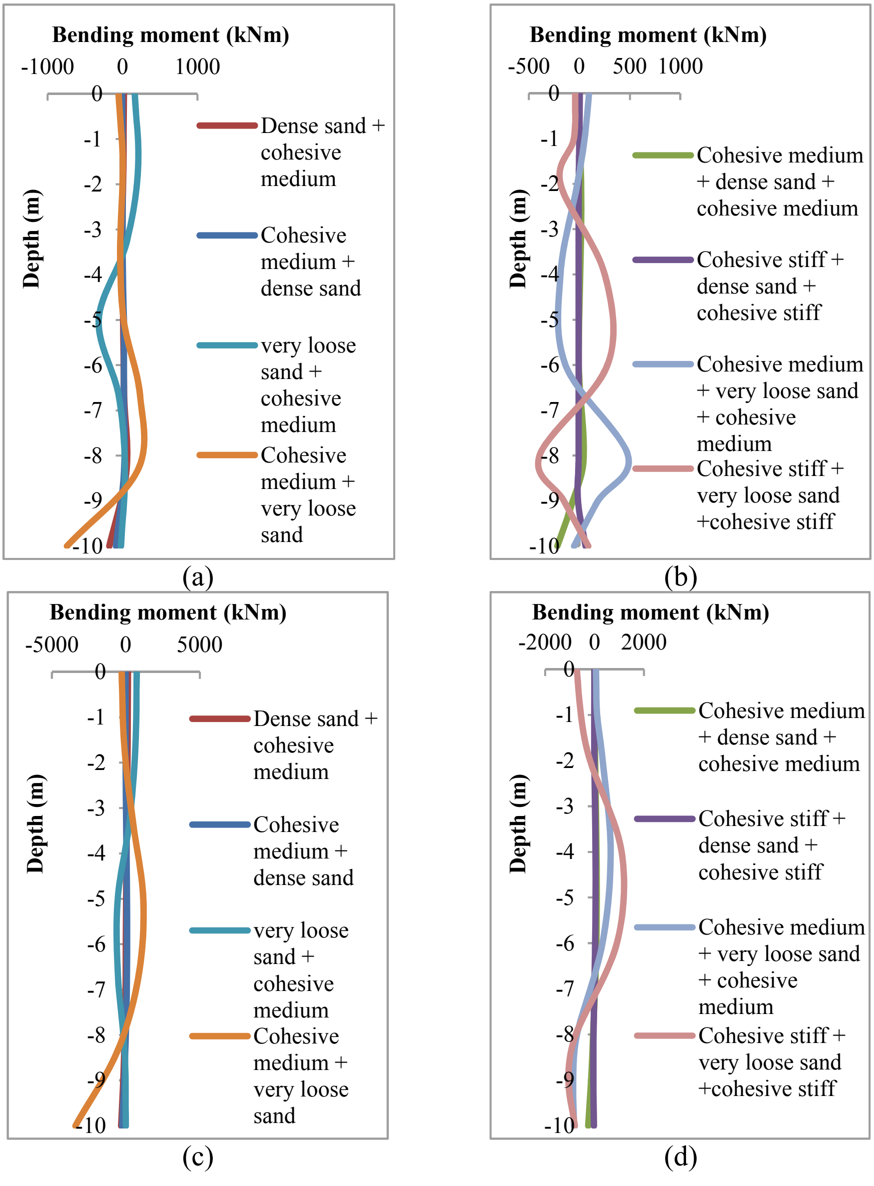

Fig. 4 Bending moment results of (**a**) 0.4 m diameter pile in double layered soil (**b**) 0.4 m diameter pile in triple layered soil (**c**) 0.8 m diameter pile in double layered soil and (**d**) 0.8 m diameter pile in tripe layered soil subjected to dynamic analysis with PGA 0.3 g

From the results of dynamic analysis, it is thus seen that bending moment witnessed by pile due to different surrounding soil conditions is influenced by the pile diameter, number of soil layers as well as with the positioning of soil types.

2.4 Pushover Analysis Results of Single Pile Embedded in Stratified Soil

The pushover analysis of pile surrounded by different soil combinations is conducted by pushing the pile until pile head displacement as obtained from dynamic analysis is achieved. Monotonically increasing horizontal load of 10 kN is applied at the pile head for static pushover analysis. Figure 5 shows the bending moment witnessed by each pile surrounded by different double layered and triple layered soil combinations due to pushover analysis.

For 0.4 m diameter pile surrounded by cohesionless dense sand placed above cohesive medium soil, the magnitude of maximum bending moment is 209.4 kN-m. The maximum bending moment reduces to 68.72 kN-m by interchanging position of the soil layers. By replacing cohesionless dense sand with cohesionless very loose sand, the maximum bending moment is 302.4 kN-m for very loose sand layer placed above cohesive medium soil layer. By interchaning of the positions of soil layers, the maximum bending moment increases to 861.5 kN-m. For triple layered cohesionless dense sand sandwiched between layers of cohesive medium soil surrounding 0.4 m diameter pile, maximum bending moment is 235.6 kN-m. By replacing cohesive medium soil with cohesive stiff soil, the maximum bending moment reduces to 83.63 kN-m. For pile surrounded by cohesionless very loose sand sandwiched between cohesive medium soil layers, the maximum bending moment is 561.5 kN-m. By replacing cohesive medium soil layer with cohesive stiff soil, the maximum bending moment is 459.6 kN-m.

For 0.8 m diameter pile surrounded by cohesionless dense sand placed above cohesive medium soil, maximum magnitude of bending moment is 1209 kN-m. By interchanging the position of soil layers, the maximum bending moment reduces to 904.7 kN-m. By replacing the cohesionless dense sand layer with cohesionless very loose sand, the magnitude of maximum bending moment is 1964 kN-m for sand layer placed above cohesive medium soil layer. By changing the position of soil layers, the magnitude of maximum bending moment increase to 4798 kN-m. For triple layered soil containing cohesionless dense sand sandwiched between cohesive medium soil layers, the maximum magnitude of bending moment is 844.9 kN-m. By replacing cohesive medium soil layers with cohesive stiff soil, the magnitude of maximum bending moment reduces to 341.7 kN-m. For cohesionless very loose sand sandwiched between cohesive medium soil layers, the magnitude of maximum bending moment is 3564 kN-m. However, by replacing cohesive medium soil layers with cohesive stiff soil, the maximum bending moment reduces to 3058 kN-m.

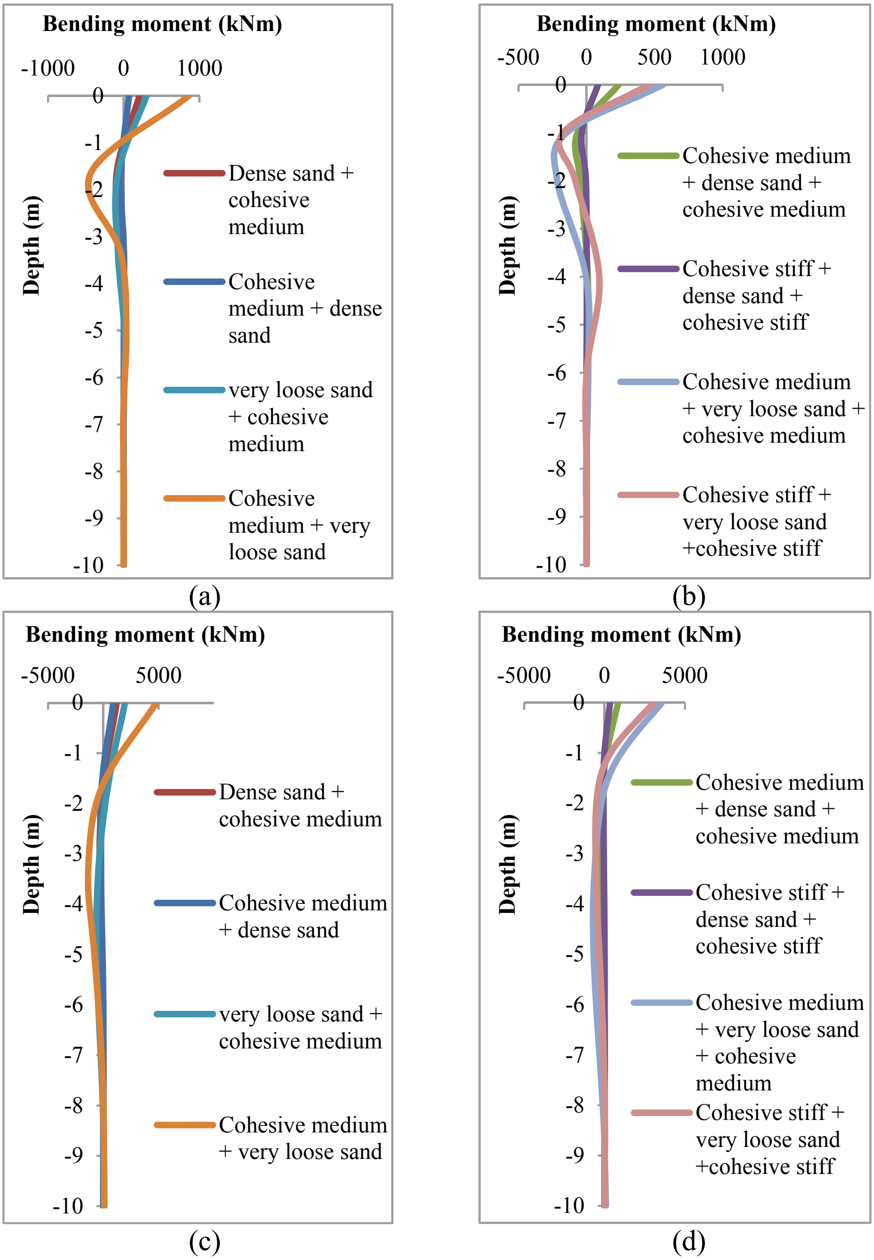

Fig. 5 Bending moment results of (**a**) 0.4 m diameter pile in double layered soil (**b**) 0.4 m diameter pile in triple layered soil (**c**) 0.8 m diameter pile in double layered soil and (**d**) 0.8 m diameter pile in tripe layered soil due to static pushover analysis

From the results of pushover analysis, it is thus seen that type of surrounding soil as well as the positioning of soil layers influence the maximum bending moment witnessed by 0.4 m as well as 0.8 m diameter pile.

2.5 Comparison of Pushover and Dynamic Analyses of Pile–Soil System

From the results of dynamic analysis and pushover analysis of 0.4 m and 0.8 m diameter piles surrounded by double layered and triple layered soil containing combinations of cohesionless soil and cohesive soil, it is observed that the surrounding soil influences the seismic response of pile. It is also observed that the bending moment profiles obtained for 0.4 m and 0.8 m diameter pile are different for both the analyses due to difference in location of load application for both the analyses. However, the magnitude of maximum bending moment witnessed by each pile is seen to be comparable for both the analyses for each surrounding soil condition. Figure 6 shows the comparison of maximum bending moment witnessed by each pile for each soil combination due to dynamic and static pushover analysis. It is seen that 0.4 m diameter pile experiences similar magnitudes of maximum bending moment for double layered as well as triple layered soils. For 0.8 m diameter pile surrounded by cohesionless dense sand sandwiched between layers of cohesive soil, dynamic analysis is seen to result in slightly higher magnitude of maximum bending moment than static pushover analysis.

Thus, from the comparison results it can be inferred that pushover analysis can estimate the maximum bending moment witnessed by pile due to dynamic analysis. Therefore it can be stated that static pushover analysis can be used to predict the maximum bending moment witnessed by pile due to seismic loading with the incorporation of soil-structure interaction.

3 Conclusion

From the analysis results and comparison of dynamic analysis and static pushover analysis of piles surrounded by startified soil, it can be concluded that:

- Pushover analysis as well as dynamic analysis results shows that the seismic response of pile embedded in stratified soil is influenced by the surrounding soil conditions.
- The type of soil and the position of soil layer influence the bending moment acting on the pile.
- Static pushover analysis can predict the magnitude of maximum bending moment witnessed by pile surrounded by stratified soil due to seismic loading.

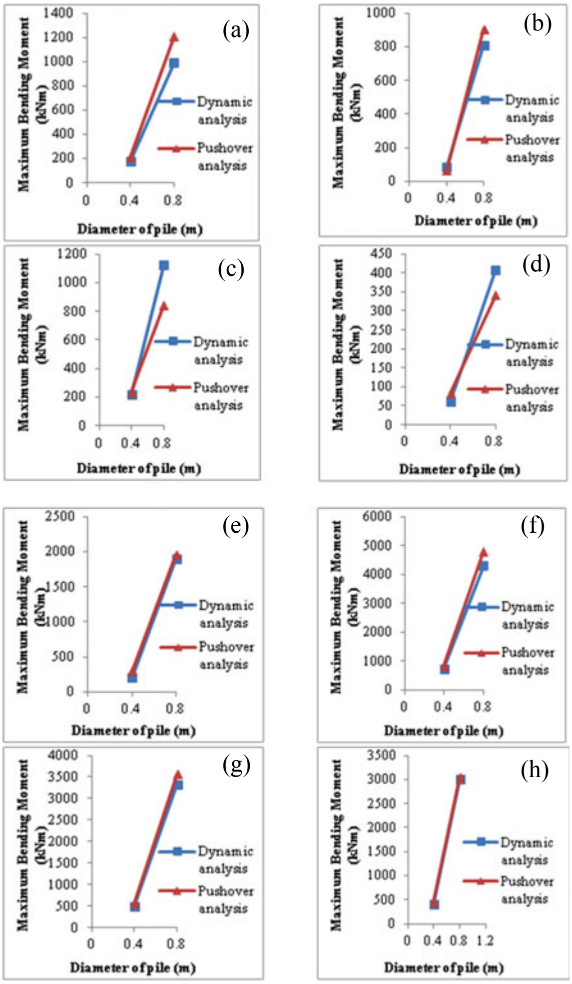

Fig. 6 Comparison of magnitude of maximum bending moment for 0.4 m and 0.8 m diameter pile surrounded by (**a**) Cohesionless dense sand + Cohesive medium soil (**b**) Cohesive medium soil + Cohesionless dense sand (**c**) Cohesive medium soil + Cohesionless dense sand + Cohesive medium soil (**d**) Cohesive stiff soil + Cohesionless dense sand + Cohesive stiff soil (**e**) Cohesionless very loose sand + Cohesive medium soil (**f**) Cohesive medium soil + Cohesionless very loose sand (**g**) Cohesive medium soil + Cohesionless very loose sand + Cohesive medium soil (**h**) Cohesive stiff soil + Cohesionless very loose sand + Cohesive stiff soil

- Static pushover analysis can be used to estimate the maximum bending moment witnessed by pile due to seismic loading with the incorporation of soil-structure interaction in place of dynamic analysis.

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