Pushover Analysis of Pile Embedded In Liquefiable and Non-Liquefiable Soil

Arup Bhattacharjee[1,*] and Bidisha Borthakur[2]
[1]Jorhat Engineering College, Jorhat, Assam, India
[2]Golaghat Polytechnic, Furkating, Assam, India
[*]corresponding author's E-mail:
bhatta_arup@yahoo.com

Abstract One of the main reasons for the collapse of bridges during an earthquake is the liquefaction of soil. In addition to the liquefaction of soil, the formation of plastic hinges on the pile can accelerate the failure of piles. Past earthquakes have resulted in the failure of piles due to the formation of plastic hinges at unexpected locations of the pile. Therefore, to predict the possible locations of plastic hinges in a pile, it is important to study the nonlinear behavior of the pile. Static pushover analysis is a method that can be conducted on piles to obtain the nonlinear behavior of a pile beyond its elastic stage. Additionally, considering soil-structure interaction during the analysis helps in obtaining a realistic response of the pile. In this research work, static pushover analysis has been conducted on single piles embedded in liquefiable and non-liquefiable soil using OpenSees PL. The advantage of conducting pushover analysis in OpenSees PL is that it enables the incorporation of soil-structure interaction, which helps to understand the influence of different types of soil on the pile subjected to incremental loading. From the results of the pushover analysis, the difference in the response of piles in liquefiable and non-liquefiable soil is studied. A pile embedded in liquefiable soil requires a lower pushover load for a specific displacement than a pile embedded in non-liquefiable soil. The bending moment developed in a pile is influenced by the type of surrounding soil. The yield moment of a pile surrounded by liquefied soil is lower than a pile in non-liquefied soil.

Keywords Numerical modeling; Pile foundation; Pushover analysis; Yield moment

Cite This Article Bhattacharjee A and Borthakur B. Pushover Analysis of Pile Embedded In Liquefiable and Non-Liquefiable Soil. Advanced Journal of Engineering. 2023,2:7-16. https://doi.org/10.55571/aje.2023015

FOUR DIMENSIONS PUBLISHING GROUP

Received: April 20, 2023 / Accepted: May 2, 2023 / Published: May 22, 2023

Introduction

There is evidence of severe damage to important structures such as bridges caused by earthquakes. The damage caused by an earthquake affects the serviceability of the bridge and ultimately disrupts normal life. Non-linear pushover analysis is an effective tool for evaluating the non-linear behavior of the bridge foundation subjected to earthquake excitation. The deformations of structures subjected to severe ground motion can be predicted by conducting static pushover analysis (Krawinkler 1996). This analysis can approximately account for the redistribution of internal forces occurring in the structure due to inertia force beyond the elastic range of the structure. The performance of the structure subjected to dynamic excitation can be predicted by conducting a pushover analysis (Krawinkler and Seneviratna 1998). Sun and Zhang (2004) predicted the maximum response of the structure along with the destruction of the structure after conducting a pushover analysis on the pier-pile-soil interaction of the bridge. The response of pile foundations in stratified liquefiable soil can be determined by applying force-based pushover analysis in OpenSees PL (Mukhopadhyay *et al.,* 2008).

The response of the pile subjected to seismic loads depends on the type of soil surrounding the pile in addition to the load from the superstructure. There is substantial literature that affirms the importance of incorporating soil-structure interaction in design to obtain an improved structure that considers the actual site effects on the structure. Zhang *et al.,* (2008) concluded that the response of a bridge foundation subjected to seismic loading is affected by the inelastic deformation of the soil surrounding the foundation. Brandenberg *et al.,* (2005) further concluded that the mode of pile deflection relative to the surrounding soil depended on the deformed shape of the soil profile, as well as the pile foundation stiffness and load from the non-liquefied crust.

It is well-known that the primary function of a pile is to transfer loads from the superstructure through weaker soil strata onto less compressible soil or rock. In addition to the load from the superstructure, the soil surrounding the piles, especially in earthquake-prone areas, influences the response of piles. Piles that are part of bridge foundations need to be designed against lateral load to prevent foundation failure when subjected to seismic forces. The main objective of this research work is to study the effect of different soil conditions on pile response when subjected to non-linear static force-based pushover analysis. In this research work, a non-linear static force-based pushover analysis has been conducted on a single 10m long fixed-head concrete pile embedded fully in different types of soils, while considering soil-structure interactions, to observe the responses.

Numerical Modeling of Soil-Pile System

The OpenSees PL is a graphical interface of OpenSees, a finite element program for non-linear static and dynamic structural analyses. The static and dynamic computations and pushover analysis can be performed using Openees PL (Wang 2015).

Pile

A 0.8 m diameter and 10 m long circular pile embedded in a soil domain are considered for numerical simulation. The soil domain comprises a single type of soil with a water table extended up to the top surface of the soil. A fixed head pile is considered for numerical simulation. The pile head is subjected to a dead load of 10 tons. The linear beam-column element is used to model the pile. The soil-pile interface is 10^4 times stiffer than pile elements both axially and flexural. The material properties used in the numerical modeling of a pile-soil system by Wang (2015) are considered in this study. The mass density of the pile is taken as 2400 kg/m3. Young's modulus is 3x10^7 kPa and the shear modulus is 1.154x107 kPa. The moment of inertia of the pile and torsion constant is 0.020106 m^4 and 0.0402123 m^4 respectively.

Soil

The four different soil types are considered to study the influence of each soil on the pile. The soil types considered are as follows: (a) saturated cohesionless very loose sand, (b) saturated cohesionless medium sand, (c) saturated cohesionless dense sand, and (d) cohesive stiff soil.
Table 5.1 presents the material model used to model different soil types.

Table 5.1. The material used in numerical modeling

Soil type	**Material model**
Silt	Pressure dependent multi yield model
Sand	Pressure dependent multi yield model
Clay	Pressure-independent multi-yield model

The details about the soil properties, fluid properties, dilatancy properties, and liquefaction properties for the saturated cohesionless soil and cohesive soil are given in Table 5.2. The water table is extended up to the pile head for liquefaction analysis.

Boundary Conditions

The boundary condition is rigid box type and fixed at the bottom in all directions. Figure 5.1 shows the half-meshed pile-soil model as modeled in OpenSees PL. The model is fixed in the Y direction and free in X and Z directions.

Table 5.2. Soil Properties

Properties		**Soil type**			
		Very loose sand	**Medium sand**	**Dense sand**	**Cohesive stiff soil**
Elastic Properties					
Saturated mass density (Mg/m^3)		1.7	1.9	2.1	1.8
Reference values	Pressure (kPa)	80	80	80	100
	Shear modulus (MPa)	55	75	130	150
	Bulk modulus (GPa)	0.15	0.2	3.9	0.75
Non-linear properties					
Friction angle (^{o})		29	33	40	0
Cohesion (kPa) multiplied by $\sqrt{(3/2)}$		0.2	0.3	0.3	75

Fluid Properties					
Fluid mass density (Mg/m^3)		1	1	1	1
Permeability (10^{-6} m/s)	Horizontal	0.66	0.66	0.66	0.001
	Vertical	0.66	0.66	0.66	0.001
Dilatancy / Liquefaction Properties					
Phase transformation angle (^{o})		29	27	27	--
Contraction parameter		0.21	0.07	0.03	
Dilation parameter 1		0	0.4	0.8	
Dilation parameter 2		0	2	5	
Liquefaction parameter 1		10	10	0	
Liquefaction parameter 2		0.02	0.01	0	
Liquefaction parameter 3		1	1	0	

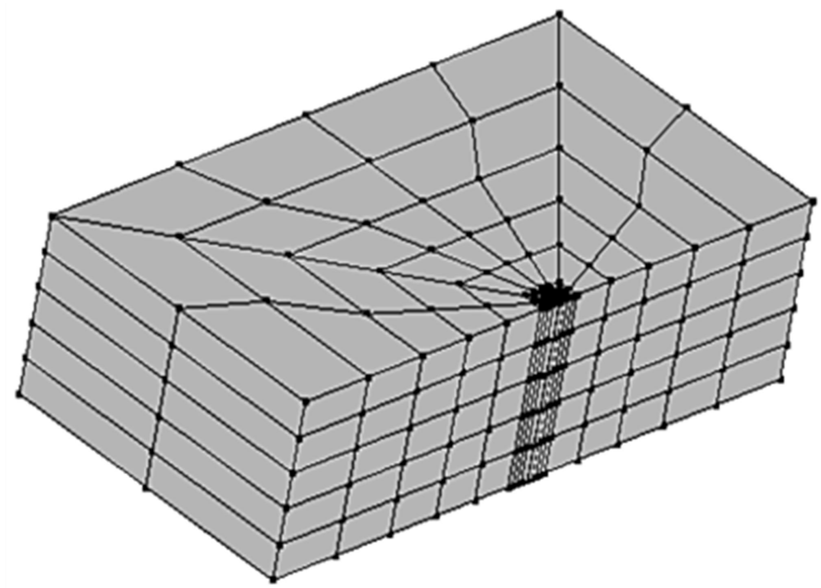

Figure 5.1. 3D view of half meshed pile-soil model in OpenSees PL

Pushover Analysis of Pile

Force-based pushover analysis is conducted on a 0.8m diameter pile by applying a stepwise incremental horizontal load of magnitude 10 kN at the pile head. The incremental horizontal load is applied until the pile head displacement reaches 0.2m, which is 2% of the pile length. The pile embedded in different types of soil requires different loading steps to reach 0.2m displacement of the pile head.

The excess pore pressure ratios of different soils increase with an increase in pushover loading. Figure 5.2 shows the variations of excess pore pressure ratio at different depths at the end of pushover loading. The maximum excess pore pressure ratio of cohesionless very loose sand is 1.43 at a depth of 1.25m, and that of cohesionless medium sand is 1. As the excess pore pressure ratio is greater than or equal to 1, the soil liquefies due to the application of pushover loading. However, the excess pore pressure of cohesionless dense sand is 0.52, implying that the soil does not liquefy on the application of pushover loading for a pile head displacement of 0.2m. For cohesive soil, which is non-liquefiable, the excess pore pressure ratio is a very low value of 0.23.

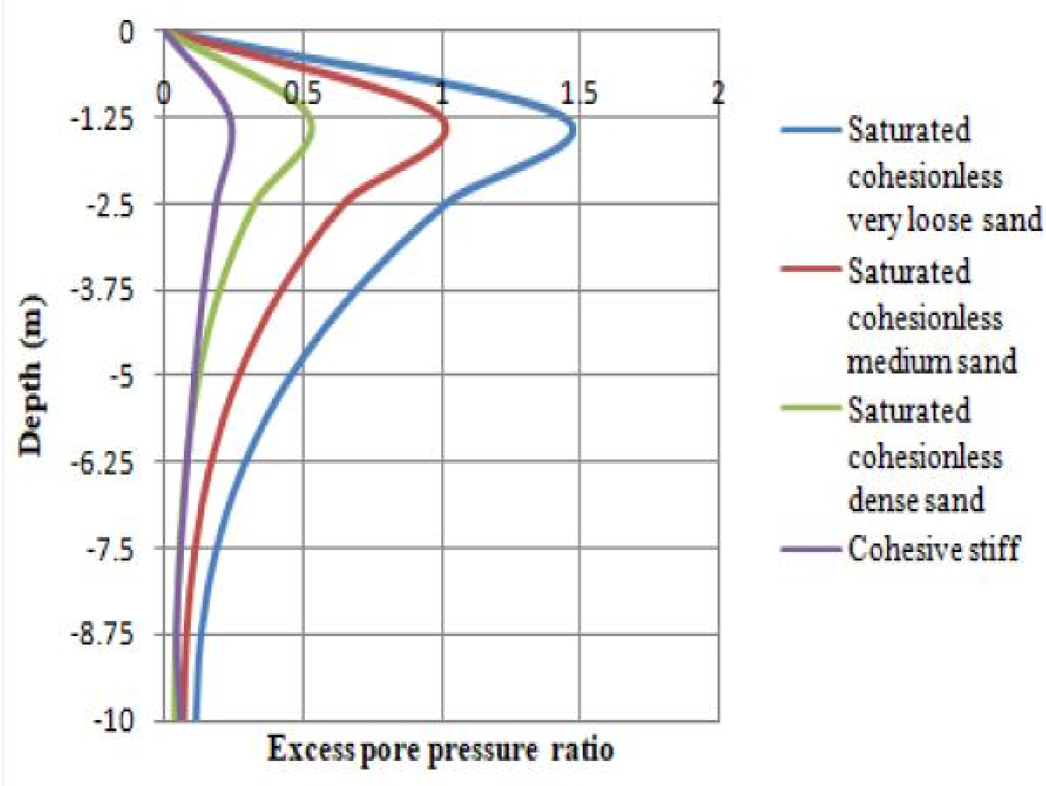

Figure 5.2. Excess pore pressure ratio-depth graph due to pushover analysis

Non-liquefiable cohesive stiff soil required the maximum number of loading steps for a pile head displacement of 0.2 m. However, the number of loading steps is lower for piles embedded in liquefiable soil as compared to non-liquefiable soil. The load versus pile displacement graphs for the pile embedded in different types of soil are shown in Figure 5.3. From the figure, it is observed that the load versus pile head displacement graph is non-linear. The pile behaves elastically under a small load, but as the load increases, the pile starts yielding, and the load-displacement curve becomes non-linear. The point on the curve that has the maximum curvature is usually referred to as the yielding point (Mukhopadhyay *et al.*,, 2008). The yield load at which the linear behavior of the pile changes to non-linear is determined by drawing double tangents. The yield load of the pile embedded in loose cohesionless soil and medium cohesionless soil is 2286 kN and 4200 kN, respectively. The yield load of the pile embedded in dense cohesionless soil and stiff cohesive soil is 5239 kN and 13103 kN, respectively. The load capacity of the pile is influenced by the density and type of the surrounding soil.

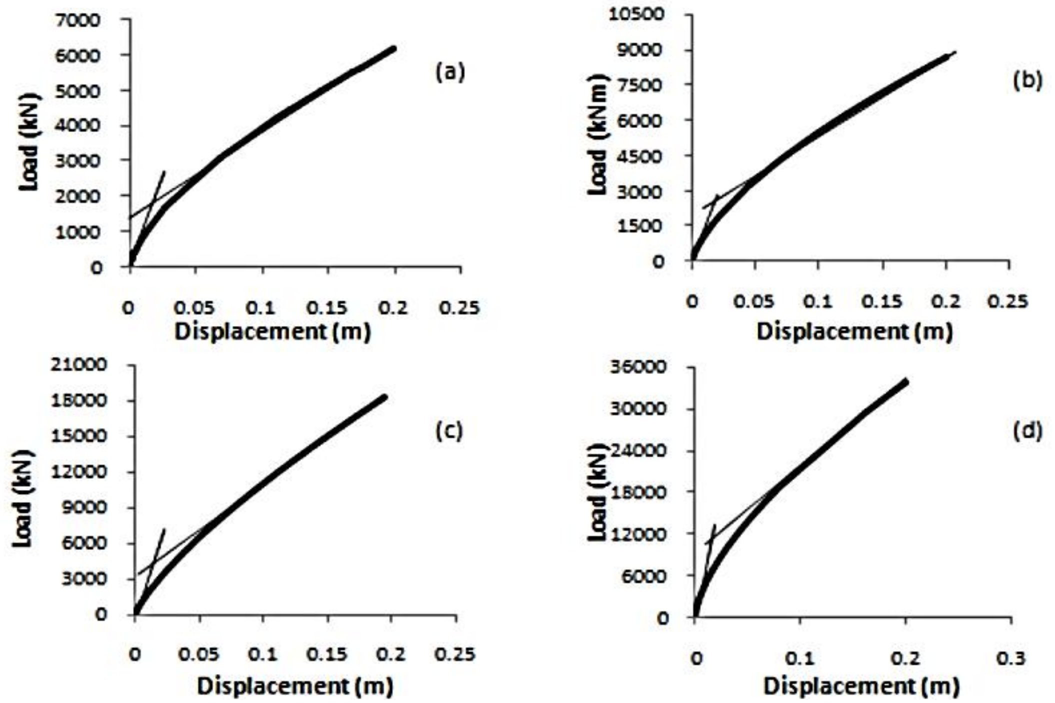

Figure 5.3. Load-displacement graph for pile embedded in (a) cohesionless very loose sand, (b) cohesionless medium sand, (c) cohesionless dense sand, and (d) cohesive stiff soil

The bending moment profile of the pile subjected to pushover loading is shown in Figure 5.4. The bending moment of the pile is maximum at the pile head for all cases of soil due to the application of load at the pile head. Piles in cohesionless very loose sand, medium sand, and dense sand are subjected to bending moments of 15504.8 kN-m, 19167 kN-m, and 28138.4 kN-m, respectively, at the pile head. The cohesive stiff soil has the highest bending moment at the pile head, with a magnitude of 39187.2 kN-m, which is more than twice the bending moment witnessed in piles embedded in cohesionless very loose sand and cohesionless medium sand.

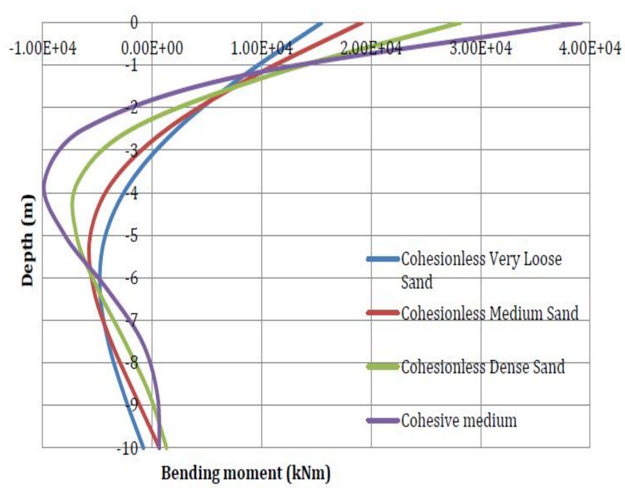

Figure 5.4. Bending moment profile of pile embedded in different types of soil

The moment-curvature graph is drawn to determine the yield moment. Figure 5.5 shows the moment-curvature curve at different depths of 1.25 m, 3.75 m, 6.25 m, and 8.75 m of the pile embedded in cohesionless very loose sand. The moment-curvature curve is non-linear at depths 1.25 m, 3.75 m, and 6.25 m. The yield moment can be determined by drawing double tangents. The yield moment of the pile embedded in very loose cohesionless soil is 1600 kN-m. The yielding of the pile will take place within depths 1.25 m and 6.25 m. The maximum bending moment of the pile is 8120 kN-m and 4850 kN-m at depths 1.25 m and 6.25 m respectively.

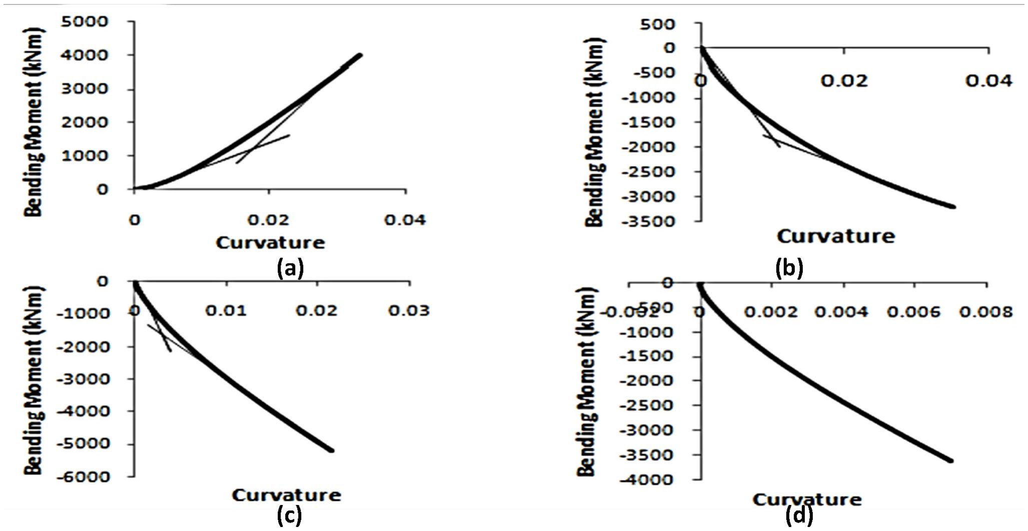

Figure 5.5. Moment curvature curve of the pile embedded in cohesionless very loose sand at depths of (a) 1.25 m, (b) 3.75 m, (c) 6.25 m, and (d) 8.75 m

Figures 5.6 and 5.7 depicts the moment-curvature relation at different depths of 1.25 m, 3.75 m, 6.25 m, and 8.75 m of the pile embedded in cohesionless medium sand and cohesionless dense sand respectively. The yield moment of the pile embedded in cohesionless medium sand and cohesionless dense sand is 2450 kN-m and 3000 kN-m respectively. In the case of a pile embedded in cohesionless dense sand yielding take place at depth of 3.75 m. The yielding moment of the pile increases with an increase in the relative density of cohesionless soil. Figure 5.8 shows the moment-curvature relationship for cohesive stiff soil. The yield moment of cohesive stiff soil is 3600 kN-m. The yielding of the pile occurs at 3.75 m depth. The yielding moment of non-liquefiable soil is more than liquefiable soil.

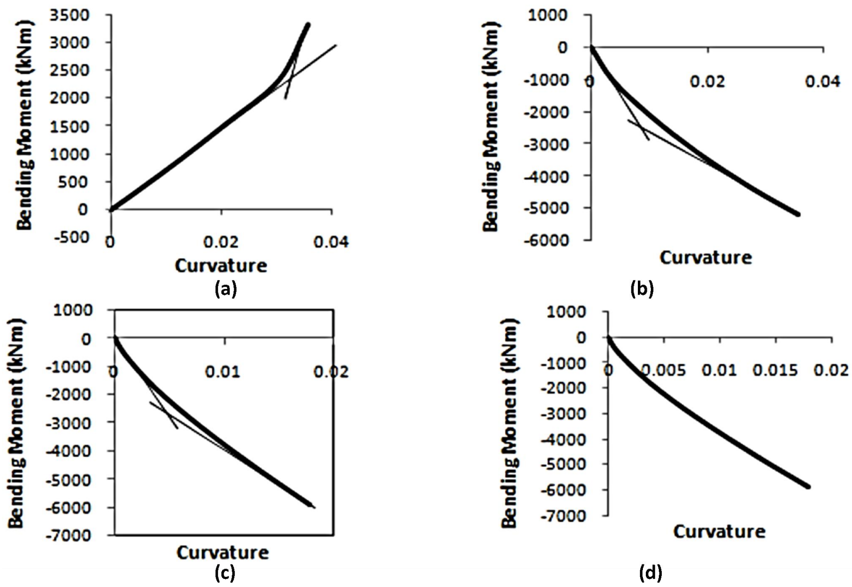

Figure 5.6. Moment curvature curve of the pile embedded in cohesionless medium sand at depths of (a) 1.25 m, (b) 3.75 m, (c) 6.25 m, and (d) 8.75 m

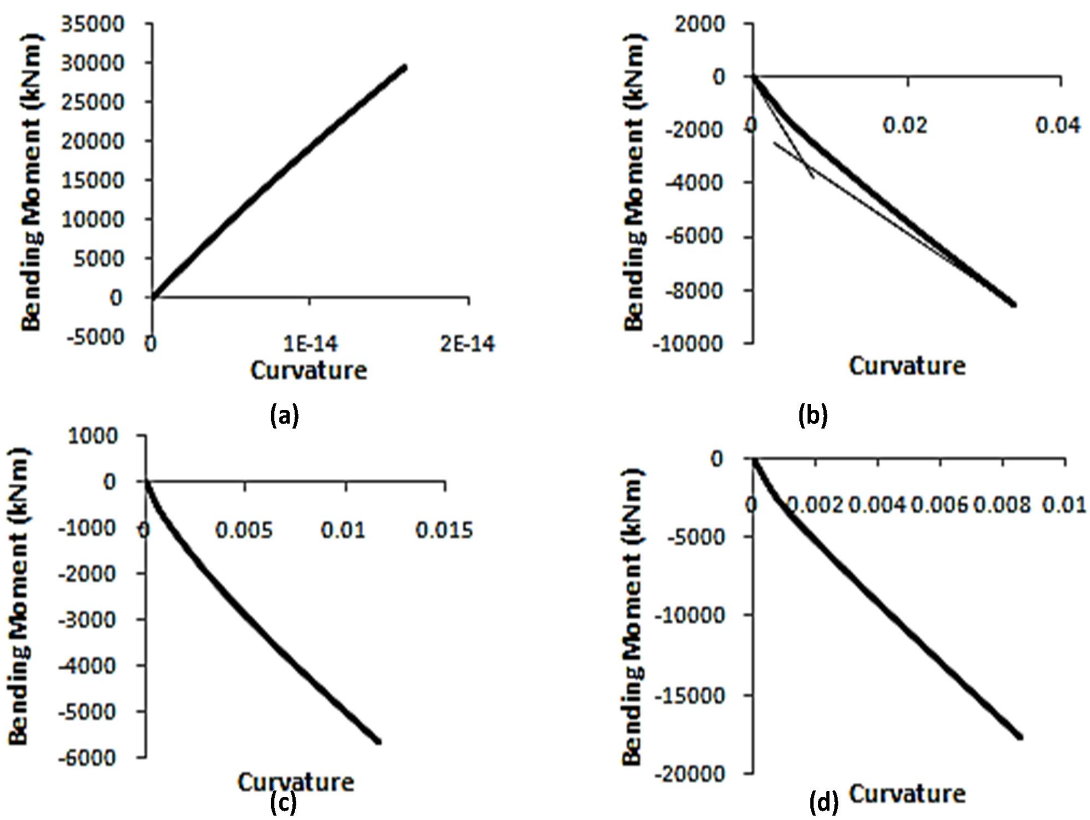

Figure 5.7. Moment curvature curve of the pile embedded in cohesionless dense sand at depths of (a) 1.25 m, (b) 3.75 m, (c) 6.25 m, and (d) 8.75 m

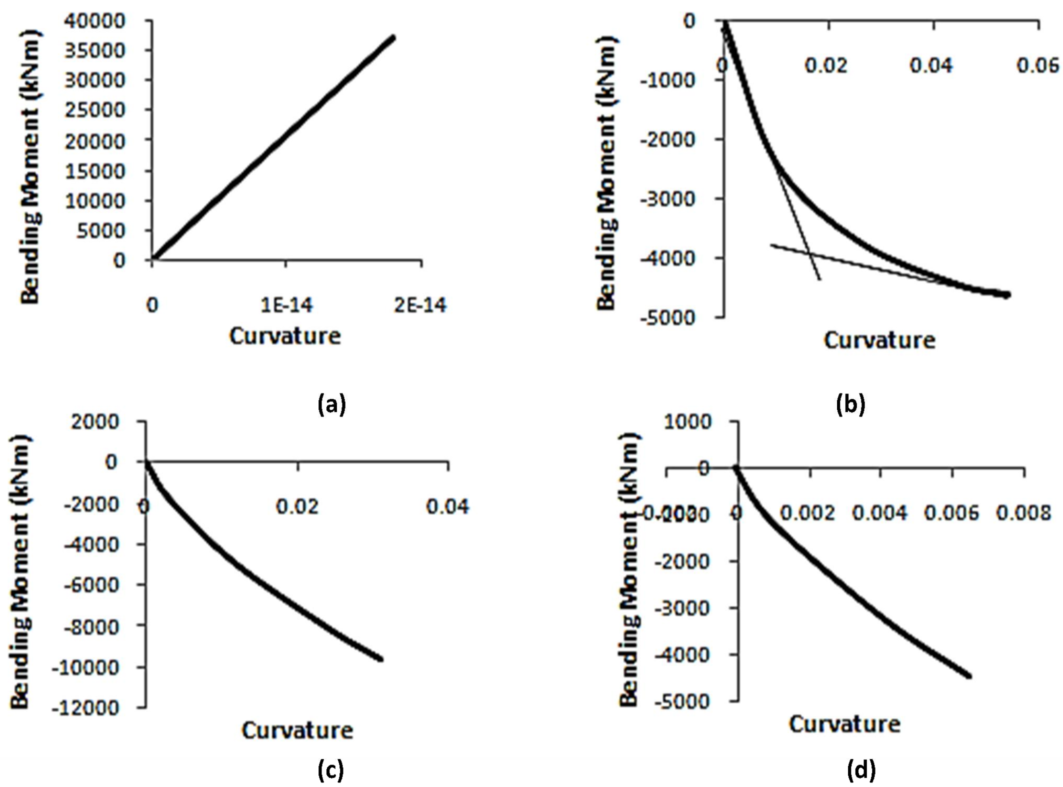

Figure 5.8. Moment curvature curve of the pile embedded in cohesive stiff soil at depths of (a) 1.25 m, (b) 3.75 m, (c) 6.25 m, and (d) 8.75 m

Conclusions

The responses of the pile for piles surrounded by liquefied soil and non-liquefied soil are investigated in this study through numerical analysis. The pushover analyses are conducted to find the effect of liquefiable soil and non-liquefiable soil on pile response. The following conclusions can be drawn from the entire investigation:

(i) The piles embedded in liquefied cohesionless very loose sand and cohesionless medium sand attained the required pile head displacement at a lesser pushover load as compared to piles embedded in non-liquefied soils.

(ii) The extent to which the pile behaved elastically is not only dependent on the load applied, but also on the surrounding soil type. The extent of elastic behavior is highest for piles embedded in cohesive medium soil followed by cohesionless dense sand and cohesionless medium sand and it is least for cohesionless very loose sand.

(iii) The bending moment is maximum at the pile head for all types of soil due to the application of load at the pile head. The bending moment of the pile surrounded by cohesive medium soil is maximum followed by the bending moment of the pile embedded in cohesionless very loose sand and cohesionless medium sand. Piles surrounded by cohesionless dense sand witnessed bending moments higher than these two soils as well.

(iv) The yield moment of a pile embedded in liquefied soil was much lower than the yield moment of a pile embedded in non-liquefied soil. The location of yielding of the pile is also affected by the surrounding soil type.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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