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Behavior of SFRC Composite Pile Resting on Sloping Ground of Cohesive and Non-cohesive Strata

Aman Tiwari[1]*, Suneet Kaur[2], and Nitin Dindorkar[2]

Abstract

Reinforced concrete piles are increasingly being utilized in situations where there is a need to transfer loads in deep strata, particularly for infrastructure projects built on sloping grounds. The present study comprises a finite element analysis (FEA) to investigate the lateral load-bearing capacity of steel fiber reinforced concrete (SFRC) pile, embedded in sloping grounds with sandy and clayey soils. The lateral load capacity of the steel fiber reinforced concrete pile is determined by analyzing the displacement and load transfer behaviour under lateral loads for both soil types. The FEA results are first validated against available experimental data on fiber reinforced concrete piles. The analysis provides insights into the pile-soil interaction and the factors affecting the lateral load capacity of the SFRC pile. The FEA results can be used to improve the design and construction of reinforced concrete pile foundations for various engineering applications on sloping grounds. The lateral load capacity of the SFRC pile is evaluated for various inclinations of the slope at three different locations along the slope. The changes in lateral load capacity for the different locations are explained in terms of percentage and relative changes for different soil profiles. The lateral load capacity for piles in cohesive soil is found to be 40–50% higher compared to non-cohesive soil. With an increase in ground slope from 30 to 60 degrees, the load capacity of the steel fiber reinforced concrete pile is observed to decrease by approximately 25%.

Keywords: Steel Fiber, Reinforced Concrete Pile, Lateral load, FEA, Deflection, Sloping Ground.

INTRODUCTION

Proper evaluation of soil-structure interaction is required for the study of the behavior of laterally loaded piles. Multistorey buildings, transmission cables, bridges, highway structures, etc. all use pile foundations to withstand axial and lateral loads. The rapid expansion of the infrastructure development creates the need to provide piles on sloping ground. The behavior of the piles installed at sloping ground largely differs from those within the horizontal ground. The reason can be attributed to the reduced passive resistance and initial confining pressure. Pile deflection and bending moment are significant factors to be considered when analysing the response of laterally loaded piles. The lateral forces acting on piles as a result of soil movement are the major source of concern in the design of pile foundations, because they have the potential to cause additional internal forces and excessive deflection on the piles. In extreme circumstances, they may cause damage to the piles, impairing the serviceability and stability of the superstructures. As a result, it is critical to assess pile responses under these circumstances. The study of the behavior of these piles have been carried out by numerous researchers, most of them considering the piles with leveled ground conditions.[1] gives a description of the results of a number of experiments that were done using a 3-D finite

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element model of a laterally loaded piles on a clayey slope. The p–y curves in the model were derived from the observations, and they were used to do so. According to the findings, the inclination of the ground has a considerable impact on the ultimate load (p_u), particularly in the vicinity of the ground surface.

To examine how a slope affects the p-y curves in dry sandy soil, an experimental investigation of the actions of laterally loaded piles was conducted [2]. According to the findings, the maximum distance at which the slope is no longer able to exert any influence is approximately 8B (B is distance of pile from the crest) for a slope with an angle of 1V:2H and 12B for a slope with an angle of 2V:3H. These numbers are almost totally unaffected by the shear strength of the sand mass on which the pile installed.

Using three-dimensional finite difference analysis, an investigation was done on the sleeved and un-sleeved piles constructed on an inclined surface by [3]. According to the findings, the primary technique by which sleeved piles transfer loads is a down shear transfer along the vertical plane.

Chae et al. illustrated the findings of various computational studies that were carried out with a 3-D finite element model test and a prototype test on rigid laterally loaded short piles and piers situated close to a 30° slope. It was noted that the lateral resistance of the piles decreased as position changed nearer to the crest of the slope.[4]

An experimental investigation was carried out on a single pile Muthukkumaran et al. to investigate the impact of the lateral deflection of pile-supported structures on unsteady slope. The findings of the tests carried out on horizontal and sloping ground have been differentiate to demonstrate the impact that sloping ground has because of lateral soil movement.[5]

The analysis of the anticipated pile response was conducted utilizing the FLAC3D software[6]. The analysis specifically targeted an embankment slope impacted by a liquefied layer beneath the embankment and an unstable soil layer above it. The results of the sensitivity experiments performed on the soil and pile characteristics indicated that the pressure that is placed on the pile and the eventual failure modes of the pile are significantly influenced by the respective stiffness of the soil and pile.

Begum and Muthukkumaran, Muthukkumaran et al. presented a 2-D finite element analysis of a flexible long pile that was placed on sloping ground of cohesionless soil and subjected to lateral pressure. When compared to the situation where the ground was level, the maximum value of the bending moment in the pile experienced an increment of 29% when the L/D ratio was 25 and the slope was 1V:2H.[7,8]

A 3-D finite element analysis was conducted in order to investigate the behavior of piles in sloped ground when subjected to an undrained lateral loading situation by Georgiadis and Georgiadis [9]. Based on the findings, a novel p–y criteria for static loads of piles in clay was proposed. This novel criterion incorporates both the slope's inclination and the adhesion at the interface of the pile and slope.

Sawant and Shukla performed an investigation into the impact of slope angles by studying the behavior of piles experiencing lateral loaded that were installed at the top of the slope [10]. The findings indicate that an increment in the slope angle leads to an increase in both the pile top displacement and the maximum moment. Sawant et al discussed about the edge distance reaction on the pile and concluded that edge distance has a negative effect on pile top displacement and bending moment.[11]

Comparative analysis with the help of experiments and numerical analysis with the use of software are performed by Yang et al. to achieve the lateral load against the deflection of the pile at various ground conditions [12]. A finite element research done by Chong et al. examines offshore monopile soil response over time in which numerical studies show that pile shapes affect lateral displacement and stress, whereas repetitive lateral load resistance rises globally.[13]

An experimental analysis has been performed to judge the lateral ability of piles resting on horizontal as well as inclined ground, and a relation for the p-y curve and reduction factor is derived by Khati & Sawant, Yuan et al [14,15].

Poorjafar et al. analyzed the pile through experimentation, where the findings indicate that although the short piles move rigidly, the soil around them is displaced over their entire length. whereas, the long piles move more flexibly along a portion of their length.[16]

Gandhi et al. highlights the potential of utilizing waste materials like quartzite and scrap tire rubber in road construction, promoting environmental sustainability and reduced consumption of conventional aggregates [17]. Bahoria et al. examines the mechanical behavior of concrete with partial replacement of tire retread fibers, exploring their potential as a sustainable alternative [18]. Key findings include reduced specific mass, decreased compressive strength over time, improved tensile strength with optimization, and reduced water absorption. These insights contribute to advancing sustainable practices in the construction sector. Palanisamy et al. explores alkali-treated Sansevieria Cylindrica fibers as reinforcement in natural rubber composites to overcome limitations like low load-bearing capacity and moisture absorption [19]. Treated fibers (up to 30%) were introduced, and the resulting composites (SCRC) exhibited improved tensile, tear properties, and hardness compared to neat rubber and untreated fiber composites. Fracture morphology of treated fiber composites was also analyzed. Murugesan et al. studied the mechanical properties of natural rubber composites reinforced with raw and alkali-treated Sansevieria cylindrica fibers [20]. The alkali treatment improved fiber adhesion and regularity, resulting in enhanced tensile strength, tear resistance, and Shore A hardness compared to composites with raw fibers and neat rubber. The treated fiber composites exhibited increases of 10.5% in tensile strength, 6.25% in tear resistance, and 6.10% in hardness.

Fiber reinforced concrete piles can be designed to meet specific project requirements by adjusting the fiber type, fiber architecture, and resin formulation. This flexibility allows for tailoring the pile's properties, such as axial and lateral load capacities, bending stiffness, and deflection characteristics.

Several research studies have been conducted to investigate the performance of fiber reinforced piles under various loading conditions and soil types. Yuan and Jia investigated mechanical properties of AR glass fibre reinforced self-compacting concrete [21]. Moon et al. investigated the lateral behavior of connections between composite piles and reinforced concrete pile caps [22]. The study evaluated various connection details and their performance under lateral loading, providing valuable insights for the design of pile-to-cap connections in pile foundations. Steel Fiber-reinforced concrete (SFRC) piles exhibit several enhanced characteristics, such as increase strength of about 20-50%, 30% higher modulus of elasticity, and 40% higher water permeability compared to normal concrete. Cracking resistance and impact load resistance are notable characteristics of SFRC and enhanced durability exhibits greater tensile and bending strength, increased ductility, and more resistance to cracking. SFRC has improved chemical stability, increased resistance to abrasion, and greater resistance to corrosion. While SFRC piles offer significant advantages, their design and installation require careful consideration of factors such as soil-pile interactions, load transfer mechanisms, and construction techniques.

When reviewing the available research, it becomes clear that various studies are available to ascertain the behavior of laterally loaded piles installed at horizontal ground, whereas more study is required to be conducted to predict the behavior of piles installed at sloping ground. As a result, it is imperative to thoroughly investigate the lateral load resistance of piles subjected to sloping ground in relation to the relative density of the soil and the depth of the pile embedded in the ground. In the present study, piles at different locations on sloping ground with three different angles of slope are considered for cohesive and non-cohesive soils to examine the behavior of piles under lateral load in the form of lateral capacity and bending moments.

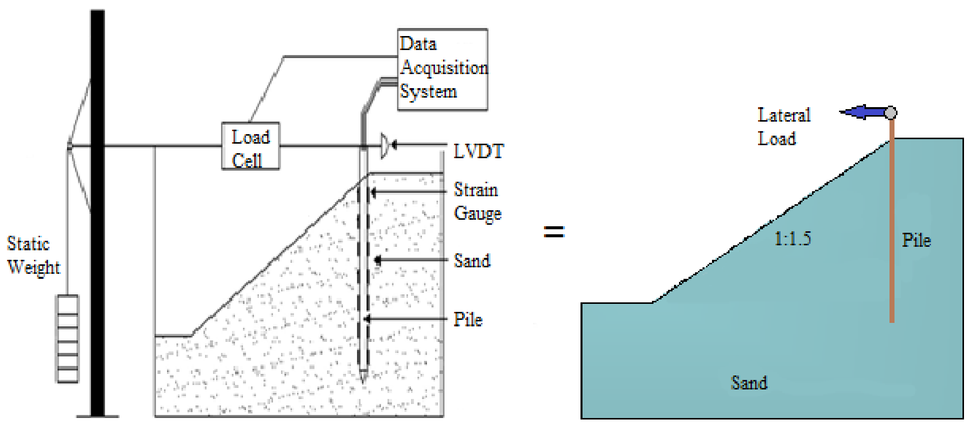
VALIDATION OF NUMERICAL MODEL

Experimental testing and finite element method (FEM) analysis are two methods used to evaluate the behavior of pile foundations for various loading conditions. Both methods have their advantages and limitations. Experimental testing provides a direct measurement of the pile behavior, but it is not only expensive and time-consuming but also difficult in terms of controlling the various parameters that are involved in the behavior. FEM analysis, on the other hand, is faster and less expensive but relies on the accuracy of input parameters and assumptions made during the analysis. To validate the results obtained from FEM analysis, it is essential to compare them with the results obtained from experimental testing. The comparison helps to identify the accuracy and reliability of the FEM model, and any discrepancies between the two methods can be analyzed and addressed. Ultimately, a combination of experimental testing and FEM analysis can provide a comprehensive understanding of the reaction of pile foundations for various loading conditions.

Prior to proceeding with the FEM analysis of the main cases considered in the present study, the validation of the analytical software PLAXIS-3D was required to be performed. The previous experimental study done by Muthukkumaran & Begam, has been simulated in the FEM analysis for the pile embedded in the sandy bed with the pile considered at the crest of the slope [23]. A series of small-scale model tests were performed on model piles placed on horizontal ground and at various slopes in order to behavior of laterally loaded piles.

The properties of the soil material used by the researchers are reproduced in Table 1. The values of required soil parameters for the Mohr's Columb Model, such as cohesion (c) and angle of internal friction (Ø), are directly used for the validation whereas the modulus of elasticity (E) and poisson's ratio (μ) values have been derived using standard correlations.

The pile has been assigned as the embedded beam, and with material type as elastic, properties of aluminum such as density are taken as 27.50 kN/m3. The lateral displacement of 50 mm was assigned at the top of the pile, as shown in Figure. 1, which also demonstrates the slope angle of 1V:1.5H. The other two variations considered for slope angle (horizontal and 1V:2H) were also simulated in the same manner.



(a) (b)

Figure 1. (a)Schematic view of experimental setup (b) Equivalent FEM Model.

Models and simulations of the mechanical responses of structures and soil are made with computational models. So, verification and validation methods are the main ways to check if a model is correct, gain confidence in it, and to believe it is reliable. The initial stage is to validate a three-dimensional numerical model based on the FEM that is appropriate for the analysis of soil-structure interaction problems and, based on validated results, further analyse different cases of piles being embedded in the sloping ground of varying slope angles. A direct method allows for a unified representation of the soil mass, the structure (pile), and the relevant boundary conditions. To get rid of the boundary effect, the distance from the side of the pile to the boundary of the model was set to be 10 times more than the diameter of the pile.

Results from both analyses are shown in Figure 2, where the curves for load versus deflection for three different conditions of ground slope, i.e., horizontal, 1V:2H, and 1V:1.5H, are drawn. The curves show a good range of agreement between the results of experimental and FEM data.

Table 1. Properties of soil used in experiment.

Property	Specific gravity (G)	Effective diameter (mm)	Uniformity coefficient	Coefficient of curvature	Unit weight (kN/ m^3)	Angle of internal friction (ø)
Value	2.68	0.23	2.70	1.07	19.10	38

In the first case, when the ground is kept horizontal, the experimental value and FEM value curves follow the same pattern, with some conservative values as far as the experimental data is concerned. Now, as the slope increases, the lateral load capacity of the pile decreases consecutively for 1V:2H and 1V:1.5H. For the second case i.e. (1V:2H), the p-y curves also move interspecifically with almost the same load capacity of the pile; similarly, in the third case i.e. (1V:1.5H), along with the flow of the curve, the ultimate load values also coincide nearly with each other. Validation of the numerical model is anticipated to be accomplished with the help of the graphs presented in Figureure 2, and the mentioned technique can be utilized to analyse different cases of piles subjected to lateral load for various conditions of soil and slope angles.

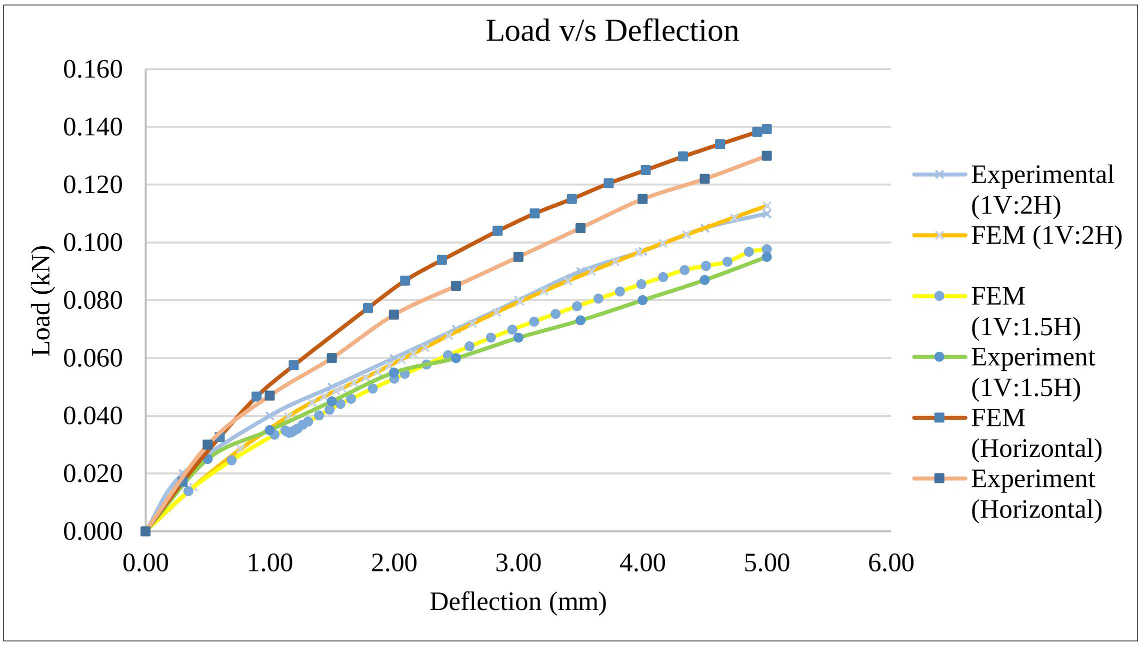


Figure 2. Comparative graphs of Experimental and FEM Analysis.

The results of the load vs deflection reported from the experimental study (for all the 3 cases considered) as compared with the results of FEM analysis are found to be having variation not more than 7%. Hence the model is considered to be validated satisfactorily.

FINITE ELEMENT ANALYSIS

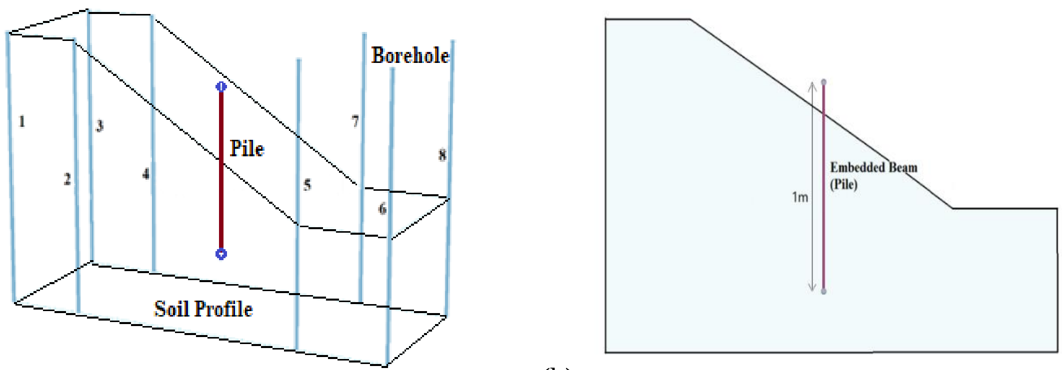
In the present study, FEA models have been made in the non-linear 3D software program "PLAXIS 3D" (version 21.00.01.7). The software is used for soil structure interaction [24], slope stability analysis [25,26], settlement analysis [27] and many other earth-related analyses. Using the above software, the geometry of the problem, such as the slope angle θ, length of pile L, and diameter of pile d, and the properties of the soil are assimilated. In particular, the analyses considered three slope angles ($\theta = 30^0, 45^0, 60^0$) and three pile locations for two different types of soil. All the considered cases are shown in Table 2, which demonstrates that a total of 18 cases were analyzed with variations in slope angle, location of the pile, and soil conditions.

The pile used in FEM analysis is a composite pile of steel fiber reinforced concrete. Composite piles provide a superior strength-to-weight ratio, possess resistance to corrosion, and demonstrate long-lasting durability. Additionally, they possess resistance to degradation and degeneration when exposed to maritime settings. These benefits can result in reduced transportation and installation expenses, as well as decreased maintenance needs during the lifespan of the pile.

Table 2. Cases with variation in soil, location of pile and slope angles.

Sand			Clay		
Location of Pile			Location of Pile		
Crest	Center	@ 2/3 from crest	Crest	Center	@ 2/3 from crest
Slope Angle			Slope Angle		
30^0	45^0	60^0	30^0	45^0	60^0

In a general condition, one pile in soil strata is made with a given embedded length, which is the length of pile inside the soil, taken as 34d (d is the diameter of pile) in the present study, and a free length, which is the length of the pile above the ground surface (which can be termed eccentric length), taken as 6d. In the first step of modelling, a soil profile with desired slopes is modelled with the use of the "borehole" property of the software, also shown in Figure 3(a), in which top and bottom coordinate points are specified along with the level of the water head (the water level in the present case is considered below the soil profile). Soil strata with sloping ground are made with eight such boreholes; at least four boreholes are required to make the single 3D geometry of a soil body. The second step comprises pile formation, which is constructed with the "Embedded beam" element, as shown in Figure 3(b), and the material is assigned as elastic.



(a) (b)

Figure 3. (a) Soil profile made with eight borehole & (b) Composite Pile made with embedded beam

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The properties of soil are then assigned to these boreholes and embedded beams, making a ground-ready soil profile. For the first case of analysis, properties of sand such as unit weight, Modulus of elasticity, Poisson's ratio, Effective cohesion, and angle of internal friction are taken into account, and similar properties are taken into account for the second case, which is of clayey strata. For pile, the first three above-stated properties are considered in both cases of analysis. The interface between pile and soil is also taken into account by considering the value as 0.5 of the interface factor (R_{inter}). Table 3 shows the properties assigned to both the soil masses and piles structured in the model. Once the modeling is done, the pile head is subjected to the desired deflection, for which the response of the pile is to be seen in view of the corresponding load and bending.

Table 3. Material properties of soil & pile used in FEM model.

Material Properties					
Soil	*Unit weight (kN/m3)*	*Young's modulus, E (MPa)*	*Poisson's Ratio (ν)*	*Effective Cohesion (C') kPa*	*Angle of Internal friction (ø)*
Sand	15.19	20.0	0.3	10.92	38^0
Clay	18.3	30.12	0.35	53.24	5^0
Pile	23	32e3	0.2	-	-

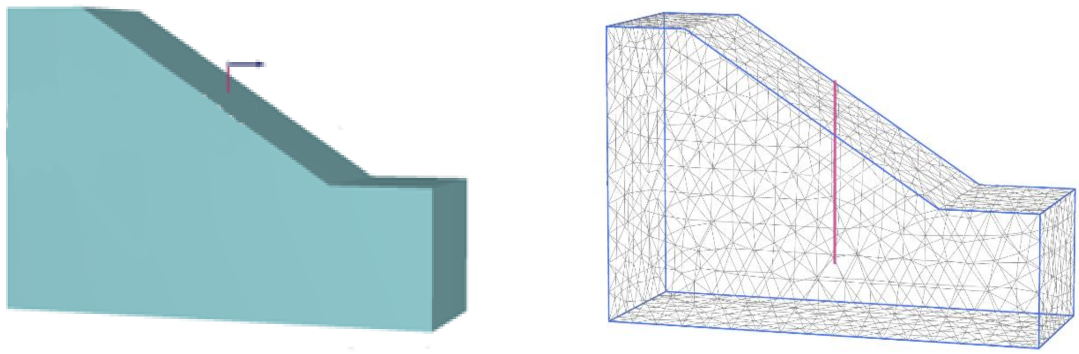


Figure 4. FEM model of pile placed in sloping ground.

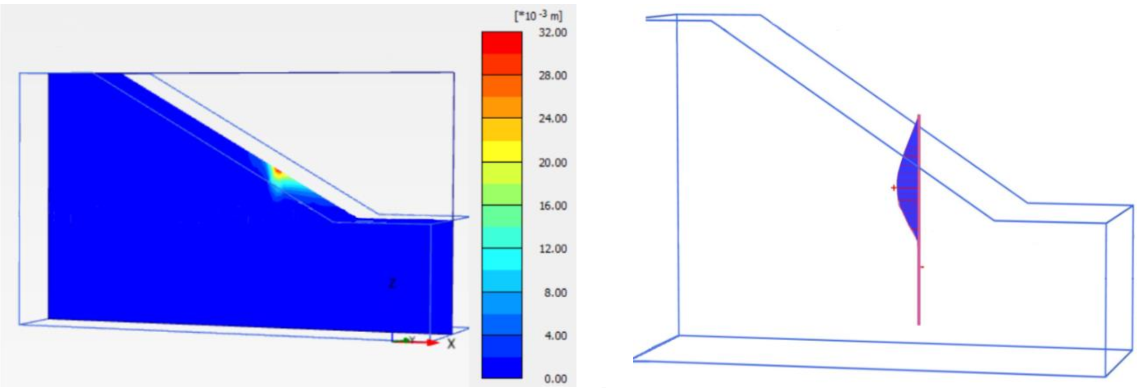
In the next stage, the model is meshed with the number nodes generated to divide the whole model into small fractions in order to solve it and achieve the best result. The mesh dimensions were chosen to be large enough to assimilate the earth slope construction. A typical 3D FE mesh and numerical model for a given case are displayed in Figure. 4. All the numerical analyses are done with an effective cohesion of c' as 10.92 kPa for sand and 53.24 kPa for clay. Several authors have proposed the Mohr-Coulomb model for capturing the yield and deformation properties of soil [28]. Therefore, the lateral responses of a pile built on a slope were simulated using that constitutive model.

RESULTS OF FEM ANALYSIS

General

Experimental results of a pile's lateral load capacity as measured by pile head deflection are initially validated using the finite element method (FEM) software PLAXIS 3D, when there is strong concordance between the outcomes. Taking these validations forward, laterally loaded piles were studied using 3D finite-element models to determine the impact of sloped ground and adhesion on their behaviour in sand and clay. The pile in the numerical model is kept at three locations on sloping ground, i.e., at the crest (β=0), at the center of the slope (β=1/2), and at two-thirds distance from the crest (β=2/3), where β being the inclined distance from the crest of the slope. For the safe design of a structure, the deflection and bending moment response are crucial design factors. PLAXIS output window is used to see the results of FEM analysis as shown in Figure. 5 (a) for deflection and Figure

5 (b) for bending moment of a particular case. The outcomes of the above analyses were applied to the development of new load-deflection (p-y) curves for piles at various sites on sloping ground of sand and clay. The p-y curve shows soil deformation at any depth below the surface, for a variation of laterally applied pressures from zero to ultimate shear, when the soil yields without further load. The p-y curves only apply to soils with a linearly rising modulus, like normally consolidated clays or sandy soils.



(a) (b)

Figure 5. FEM output showing (a) deflection map (b) Bending moment curve

Behaviour of Pile on Different Soil Conditions

The findings demonstrate that the pile that is embedded in clayey soil exhibits greater resistance to lateral load, as depicted in Figure 6, which displays the maximum load for each soil condition. The maximum load capacity for each ground slope scenario is greater for clay as compared to sand. The results indicate that the maximum load of 1.95 kN was achieved for a slope angle of 30° when clay was utilized as the supporting medium. Conversely, the minimum load of 0.75 kN was observed for a slope angle of 60° when sand was employed as the supporting medium.

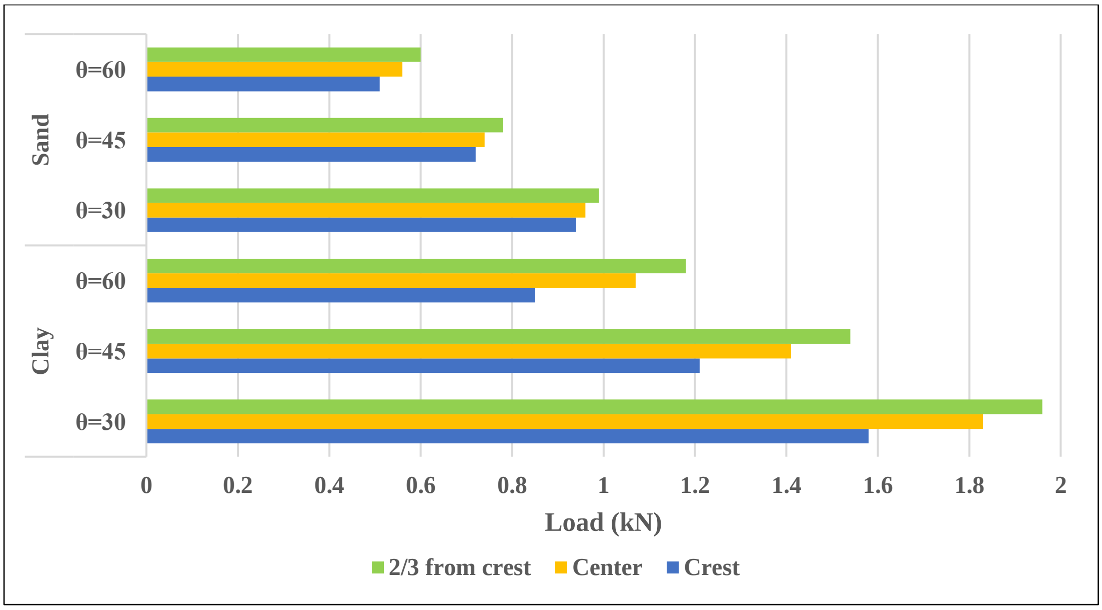


Figure 6. Maximum load values under given deflection for all cases.

It has been observed from the results that the percentage change in the load capacity gets changed by 40% in the case of the crest location, while it is 47% and 49% in the case of the center and 2/3rd location of the pile, respectively. Figure 7 shows the curves for load capacity for both soil profiles with piles installed at the center location. It has been observed that for clay strata, the lateral load capacity of = 60° almost coincides with the capacity of = 30° for sand strata, and this pattern has been seen in all the cases.

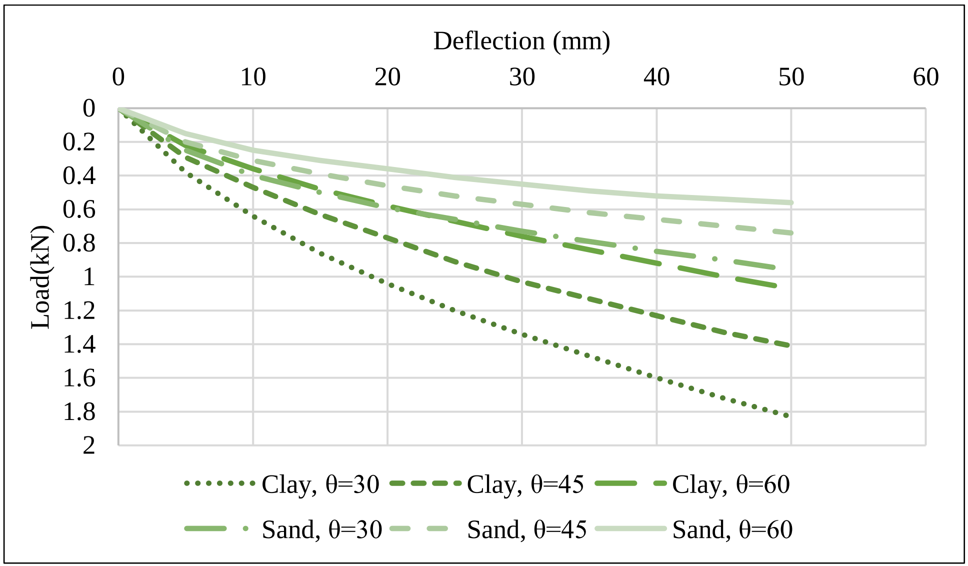


Figure 7. Comparison of loads for same location (center) for different soils

Effect of Slope Angle

The lateral strength of soil is negatively affected by an increase in slope angle. In all cases of clayey and sandy soil, the value of lateral resistance provided for the pile decreases as the slope angle increases. Table 4 illustrates the variation in maximum lateral load with respect to slope angle. The lateral load capacity exhibited a percentage change of 21-23% for both clay and sand when the angle increased from 30° to 45°. Similarly, the percentage change in lateral load capacity was observed to be in the range of 23-29% when the angle was varied from 45° to 60°. Figure 8 shows the comparison with respect to the difference in load pattern when piles are embedded in sand at the center of the slope with variation in slope angles.

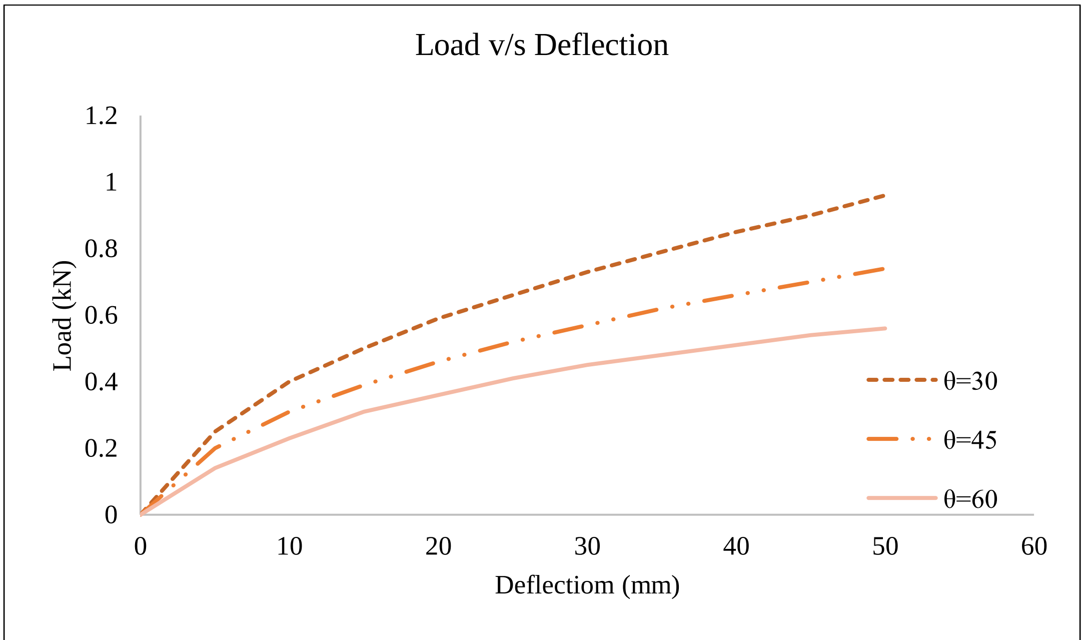


Figure 8. Comparison of loads for same location (center) for different slope angle.

Table 4. Change in maximum lateral load for various slope angle.

	Sand		**Clay**	
Case	**Change of angle from 30 to 45**	**Change of angle from 45 to 60**	**Change of angle from 30 to 45**	**Change of angle from 45 to 60**
Crest	23%	29%	23%	29%
Center	23%	24%	23%	24%
2/3 from crest	21%	23%	21%	23%

Effect of Pile Location

The present investigation involved the placement of the pile at three distinct locations along the slope, specifically at the crest, center, and two-third distance from the crest. Lateral load capacity of a pile is influenced by its location, as depicted in Table 5. The data indicates that, for a given slope angle, the lateral load values are at their minimum when the pile is installed at the crest, while the maximum lateral load value is observed when the pile is located at a distance of 2/3 from the crest. The impact of the location exhibited a greater magnitude in instances where clay served as the embedded medium, as compared to sand as the embedded medium. In Figure. 9, the curve shows the variation of load against deflection for the condition when the pile is installed at a slope of 45^0 considering the three different locations of installation, i.e., at the crest, at the center, and near the toe of the slope (2/3rds from the crest).

Table 5. Change in maximum lateral load for various location of pile.

	Sand		**Clay**	
	Crest to Center	*2/3rd to Center*	*Crest to Center*	*2/3rd to Center*
θ=30	2-3%	3-4%	13-14%	6-7%
θ=45	3-4%	5-6%	14-15%	8-9%
θ=60	7-8%	6-7%	19-20%	9-10%

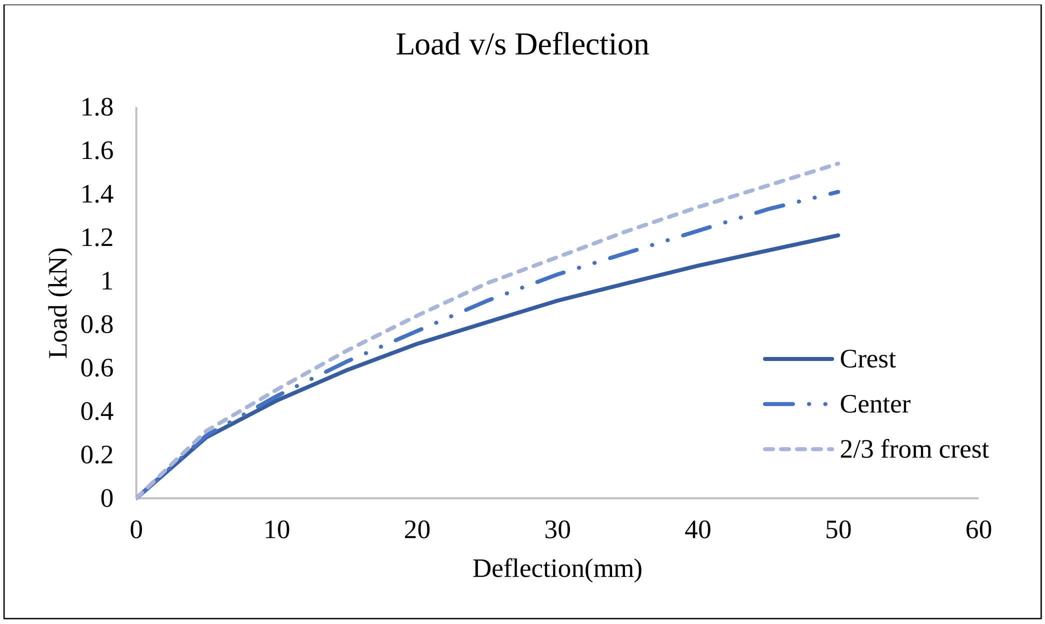


Figure 9. Comparison of loads for same slope angle (θ=45) for different locations of pile.

Bending Moment

Along with the deflection of pile for sand and clay, another significant criterion is bending of the pile, which is also examined here for the given set of conditions as shown in Figure.10. θa is for the crest, θb is for the center and θc is for the near-toe location of the pile.The bending moment is measured along the pile and plotted against the depth of the pile. In almost every case, the pattern of the bending moment as it curves with depth is almost the same. But the values of bending moments change depending on the ground surface. In the figure it can be seen that as the lateral force increases, the depth of the point of fixity (the point at which the bending moment is maximum) decreases. It is also determined that an increase in lateral load leads to a greater maximum bending moment.

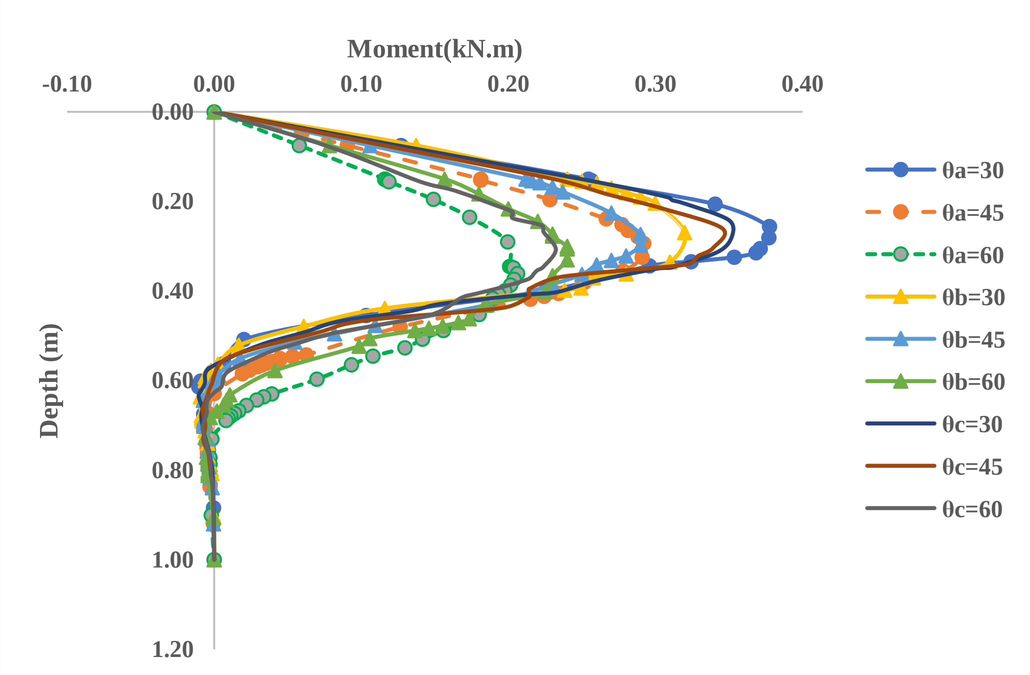


Figure 10. Bending moment variation along the pile length for clayey soil.

CONCLUSION

In this study, the behavior of a single SFRC pile installed into the slopes of clay and sand strata under lateral loads is analyzed. This objective was reached by performing a number of 3D finite element studies on piles set into the ground at varying angles and locations of slope.

The following major inferences can be made from this numerical analysis:
When a level surface becomes sloping, the lateral load capacity of the SFRC pile decreases significantly. The pile can sustain more load on the horizontal surface of the ground than on the sloped surface.

- The load-bearing capacity of the soil decreases significantly with each degree of slope. Change of 21-23% for both clay and sand as the angle shifted from 30° to 45°, and 23-29% as the angle shifted from 45° to 60°.
- Minor changes ranging from 2% to 7% were observed for sand strata when the location of the pile and slope angle were altered, whereas a greater percentage was observed for clayey strata.
- For the crest, center, and near-toe conditions, the lateral load capacity of clay is 1.70, 1.90, and 2.0 times that of sand, respectively.
- The distribution of bending moment along the length of the pile follows a similar pattern regardless of slope angle or even on horizontal ground. The bending moment in a pile will always initially increase with increasing pile depth, and will quickly approach its maximum value after the pile reaches its complete depth. The moment of bending will decrease linearly with depth until it reaches zero, at which point it will remain constant until the end of the mound.

Additionally, it can be concluded that only the lateral behavior of a loaded pile on a slope is also dominated by the mobilization of the soil above the pile to a certain depth, but a larger lateral load will drive the soil resistance below the pile.

REFERENCE

1. Brown DA, Shie CF. Some numerical experiments with a three dimensional finite element model of a laterally loaded pile. Computers and Geotechnics. 1991 Jan 1;12(2):149-62. https://doi.org/10.1016/0266-352X(91)90004-Y
2. Mezazigh S, Levacher D. Laterally loaded piles in sand: slope effect on py reaction curves. Canadian Geotechnical Journal. 1998 Jun 1;35(3):433-41. https://doi.org/10.1139/t98-016
3. Ng CW, Zhang LM. Three-dimensional analysis of performance of laterally loaded sleeved piles in sloping ground. Journal of Geotechnical and Geoenvironmental Engineering. 2001 Jun;127(6):499-509. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:6(499)
4. Chae KS, Ugai K, Wakai A. Lateral resistance of short single piles and pile groups located near slopes. International Journal of Geomechanics. 2004 Jun;4(2):93-103. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:2(93)
5. Muthukkumaran K, Sundaravadivelu R, Gandhi SR. Effect of sloping ground on single pile load deflection behaviour under lateral soil movement. InProceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, August 2004 Aug 1 (pp. 1-6).
6. Martin GR, Chen CY. Response of piles due to lateral slope movement. Computers & structures. 2005 Mar 1;83(8-9):588-98. https://doi.org/10.1016/j.compstruc.2004.11.006
7. Begum NA, Muthukkumaran K. Numerical modeling for laterally loaded piles on a sloping ground. InProceedings of the 12th International Conference of International Association for Computer Methods and Advances in Geomechanics,(IACMAG), Goa, India 2008 Oct 1 (pp. 1-6).
8. Muthukkumaran K, Sundaravadivelu R, Gandhi SR. Effect of slope on py curves due to surcharge load. Soils and foundations. 2008;48(3):353-61. https://doi.org/10.3208/sandf.48.353
9. Georgiadis K, Georgiadis M. Undrained lateral pile response in sloping ground. Journal of geotechnical and geoenvironmental engineering. 2010 Nov;136(11):1489-500. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000373
10. Sawant VA, Shukla SK. Three-dimensional finite element analysis of laterally loaded piles in sloping ground. Indian Geotechnical Journal. 2012 Dec;42:278-86. https://doi.org/10.1007/s40098-012-0022-6
11. Sawant VA, Shukla SK. Effect of edge distance from the slope crest on the response of a laterally loaded pile in sloping ground. Geotechnical and Geological Engineering. 2014 Feb;32:197-204. https://doi.org/10.1007/s10706-013-9694-7
12. Yang MH, Deng B, Zhao MH. Experimental and theoretical studies of laterally loaded single piles in slopes. Journal of Zhejiang University-SCIENCE A. 2019 Nov;20(11):838-51. https://doi.org/10.1631/jzus.A1900318
13. Chong SH, Shin HS, Cho GC. Numerical analysis of offshore monopile during repetitive lateral loading. Geomechanics and Engineering. 2019;19(1):79-91. https://doi.org/10.12989/gae.2019.19.1.079
14. Khati BS, Sawant VA. Experimental study of laterally loaded pile group in square arrangement near sloping ground. International Journal of Geomechanics. 2021 Feb 1;21(2):04020257. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001911
15. Yuan B, Li Z, Zhao Z, Ni H, Su Z, Li Z. Experimental study of displacement field of layered soils surrounding laterally loaded pile based on transparent soil. Journal of Soils and Sediments. 2021 Sep;21(9):3072-83. https://doi.org/10.1007/s11368-021-03004-y
16. Poorjafar A, Esmaeili-Falak M, Katebi H. Pile-soil interaction determined by laterally loaded fixed head pile group. Geomechanics and Engineering. 2021;26(1):13-25. https://doi.org/10.12989/gae.2021.26.1.013
17. Gandhi S, Roji SS, Motta M, Nalawade RR, Khan MA, Palanisamy S. Analysis of potential incorporation of waste into asphalt pavements. Materials Today: Proceedings. 2024 May 18. https://doi.org/10.1016/j.matpr.2024.05.097
18. Bahoria BV, Ranjith A, Laxmaiah G, Raj SS, Padhi MR, Palanisamy S. Verification of the mechanical behavior of concrete with partial replacement of the fiber resulting from tire retreading. Materials Today: Proceedings. 2024 Apr 25.

https://doi.org/10.1016/j.matpr.2024.04.067
19. Palanisamy S, Murugesan TM, Palaniappan M, Santulli C. Characterization of an eco-friendly rubber composite material based on Sansevieria cylindrica fibers. Materials Today: Proceedings. 2023 Aug 21. https://doi.org/10.1016/j.matpr.2023.08.202
20. Murugesan TM, Palanisamy S, Santulli C, Palaniappan M. Mechanical characterization of alkali treated Sansevieria cylindrica fibers–Natural rubber composites. Materials Today: Proceedings. 2022 Jan 1;62:5402-6. https://doi.org/10.1016/j.matpr.2022.03.609
21. Yuan Z, Jia Y. Mechanical properties and microstructure of glass fiber and polypropylene fiber reinforced concrete: An experimental study. Construction and Building Materials. 2021 Jan 10;266:121048. https://doi.org/10.1016/j.conbuildmat.2020.121048
22. Moon J, Lehman DE, Roeder CW, Lee HE, Lee TH. Analytical evaluation of reinforced concrete pier and cast-in-steel-shell pile connection behavior considering steel-concrete interface. Advances in Materials Science and Engineering. 2016 Jan 1;2016.
23. Muthukkumaran K, Almas Begum N. Experimental investigation of single model pile subjected to lateral load in sloping ground. Geotechnical and Geological Engineering. 2015 Aug;33:935-46. https://doi.org/10.1007/s10706-015-9875-7
24. El Hoseny M, Ma J, Dawoud W, Forcellini D. The role of soil structure interaction (SSI) on seismic response of tall buildings with variable embedded depths by experimental and numerical approaches. Soil Dynamics and Earthquake Engineering. 2023 Jan 1;164:107583. https://doi.org/10.1016/j.soildyn.2022.107583
25. Lin HD, Wang WC, Li AJ. Investigation of dilatancy angle effects on slope stability using the 3D finite element method strength reduction technique. Computers and Geotechnics. 2020 Feb 1;118:103295. https://doi.org/10.1016/j.compgeo.2019.103295
26. Sysala S, Tschuchnigg F, Hrubešová E, Michalec Z. Optimization variant of the shear strength reduction method and its usage for stability of embankments with unconfined seepage. Computers & Structures. 2023 Jun 1;281:107033. https://doi.org/10.1016/j.compstruc.2023.107033
27. Jaiswal A, Kumar R. Finite element analysis of granular column for various encasement conditions subjected to shear load. Geomechanics and Engineering. 2022;29(6):645-55. https://doi.org/10.1155/2023/5039439
28. Yuan B, Sun M, Wang Y, Zhai L, Luo Q, Zhang X. Full 3D displacement measuring system for 3D displacement field of soil around a laterally loaded pile in transparent soil. International Journal of Geomechanics. 2019 May 1;19(5):04019028. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001409

