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Numerical Study on the Effect of Rock-Socketing on Laterally Loaded Piles in the Proximity of Sloping Ground

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Abstract. Pile foundations are constructed to support structures such as offshore wind turbines, berthing structures, and transmission towers, which are subjected to large lateral loads. Such structures are susceptible to be constructed in the vicinity of sloping ground. Prior research has presented that the effect of slope induces a decrease in the lateral load capacity of the piles embedded in the neighbourhood of sloping ground. This paper explores rock-socketing as a viable solution for the betterment of lateral load capacity of piles situated in the vicinity of such sloping terrains. Parametric numerical analyses have been conducted by varying the position of the pile with respect to the crest of the slope and the depth of rock-socketing of the pile on finite-element software PLAXIS 3D. Full-scale field test data presented in respected publications have been adopted for the modeling of the prototype pile, the multi-layered soil strata, and validation of the model. A critical slope of 1V:1.5H of the soil strata has been considered for the study. The positions of the pile were considered at increments of 3 pile diameters on either side of the slope's crest. Five positions on the embankment (+3D, +6D, +9D, +12D, and +15D), and three positions on the slope (-3D, -6D, and -9D). The position of the pile embedded on the crest (0D) was also considered. The depth of rock-socketing was considered in increments of one pile diameter from the bottom of the pile (1D, 2D, and 3D). The generated load-deflection responses have been compared to un-socketed piles (US) tested in identical conditions and piles tested on uninfluenced horizontal ground. Based on the results, it was observed that the rock-socketing of piles significantly improved the lateral load capacity of the piles, and the zone of influence due to the effect of slope decreased with the increase in depth of rock-socketing.

Keywords: Laterally loaded piles; Numerical modelling; Rock-socketing; Effect of slope; Plaxis 3D.

1 Introduction

Pile foundations are designed primarily to transfer the axial loading from the superstructure onto the soil strata. However, in cases of high rise buildings, transmission towers, offshore wind turbines, and other such structures that are susceptible to large lateral loads, the pile foundations are to be designed to sustain lateral loads as well. The structural properties of the pile and the properties of the soil strata at the site are both factors that affect the lateral load capacity of the pile.

The study of laterally loaded piles was first presented by Reese and Matlock [1]. They extended Hetenyi's [2] derivation assuming the pile as a beam and considering a linear increment of the modulus of subgrade reaction with depth. Broms [3] presented solutions for the ultimate lateral resistance of a pile assuming the distribution of lateral soil pressure. Davidson [4] presented the normal stress variation in the soil surrounding the pile subjected to lateral load. This was furthered by Reese and Van Impe [5], who presented two different models for the passive wedge formation in sand and clay soil. Certain modifications to the passive wedge theory for the application of it on slopes were further presented by Reese et al. [6].

Researchers have established that a decrease in the lateral load capacity of piles has been observed when they are tested in the vicinity of a sloping ground (Mezazigh and Levacher [7]; Muthukkumaran et al. [8]; Begum and Muthukkumaran [9]; Muthukkumaran [10]; Rathod et al. [11]). This effect has been termed as the effect of edge distance. Therefore, it is necessary to identify appropriate solutions to facilitate the better efficiency of the pile foundations installed in the vicinity of sloping ground.

In general, rock-socketing is a technique that has been adapted when the soil stratum appears considerably weak to take on the design loads. IS 14593:1998 [12] recommends a depth of socketing of the pile in the range of one to four times the pile diameter with respect to the type of rock to improve the lateral load capacity. Carter and Kulhawy [13] presented parametric solutions from which closed-form solutions may be derived for various loading conditions and rock stiffness. Reese [14] developed for the analysis of a single pile socketed in a weak rock considering the non-linearity of the rock mass surrounding by assuming series of springs of soil or rock along the length of the pile based on the p-y curve approach. Muthukkumaran and Prakash [15] presented based on a parametric experimental study that increasing the depth of socketing significantly increases the lateral load-carrying capacity of the pile. Nandhagopal and Muthukumaran [16] performed model experiments on rock-socketed piles installed in the vicinity of the slope created using single-layered loose sand. Based on the results, it was concluded that rock-socketing of piles produced a significant increase in the lateral load capacity of the pile, in turn negating the decrease of it due to the effect of edge distance.

Desai and Appel [17] first developed a general finite element procedure for the analysis of laterally loaded piles. The soil behaviour was assumed to be linearly elastic, and the pile was modelled as a 1D beam element. The interaction between the pile and the soil was modelled using a thin-layer element. Yang and Jeremi [18] used FE methods to study the behaviour of laterally loaded piles on layered soil. A simple Von-Mises material model and a Drucker–Prager model were concluded to best model the clay and sand soils with acceptable accuracy, respectively. Chae et al. [19] reaffirmed the decrease of lateral load capacity of piles in the vicinity of sloping ground based on model and prototype 3D FEM analyses. Georgiadis and Georgiadis [20, 21] studied laterally loaded piles on cohesive slopes based on 3D FEM tests. They concluded that the piles of L/D =10 – 20 on a sloping ground of 45° were unaffected by the effect of the slope beyond a distance of 6 pile diameters.

Karthigeyan S et al. [22] studied the influence of depth of socketing on the behaviour laterally loaded short piles using 3D FEM techniques. It was observed that the lateral load capacity attained a constant value after a significant increase. Karthigeyan S and Rajagopal K [23] conducted 3D FEM analysis on rock-socketed piles embedded in cohesionless soil overlying rock. It was concluded that the effect of depth of socketing might not be significant on long piles where the depth of soil is significant to resist the lateral load.

From the literature study, it can be observed that there is very limited published literature related to the laterally loaded rock-socketed piles in the multi-layered soil or the vicinity of sloping ground. Therefore, in this paper, the results of parametric numerical analyses performed on a full-scale laterally loaded rock-socketed pile modelled onto a multi-layered soil in the vicinity of sloping ground have been discussed. The response of the rock-socketed piles has been compared to the same piles tested on undisturbed horizontal ground and un-socketed piles modelled and tested in identical conditions. The position of the pile and the depth of socketing have been used as variable parameters.

2 Numerical Model

All finite element analyses in the parametric study were performed by using the 3D finite element program PLAXIS 3D. The pile, soil strata, and their properties have been derived from the full-scale lateral load field test presented by Ismael [24]. The pile was modelled using the embedded beam tool as a linearly elastic body. The embedded beam elements are 3-node line elements with six degrees of freedom. The soil was modelled using the Hardening small strain (HS-small) model as it considers both stress and strain dependency of the soil. The soil model used 15 node-wedge elements having six stress points, which gives an ample number of locations for the accurate measurement of the stress-strain behaviour of the pile along with its embedded depth. The pile-soil interface has been modelled using the interface element (R_{inter}), which recreates the ideal friction in the system. The rock was modelled using a simple Mohr-Coulomb (MC) model. The medium-mesh has been adapted throughout the study based on a convergence study. The properties used for the modelling of this soil-rock stratum are given in Table 1.

Table 1. Properties of the soil-rock stratum

Properties	Soil Layer 1	Soil Layer 2	Rock
Material Model	HS-Small	HS-Small	MC
Material Behaviour	Drained	Drained	Drained
Unsaturated unit weight (Υ_{unsat}) (kN/m^3)	18.7	19.5	28
Young's Modulus (E) (kN/m^2)	3.5E+4	5.0E+4	5.0E+6
Poisson's ratio (√)	0.34	0.3	0.21
Cohesion (c) (kN/m^2)	20	0.1	500
Friction Angle (Φ)	35	43	27

Dilatancy angle (ψ)	5	13	-
Interface factor (R_{inter})	0.9	0.9	0.9

3 Parametric Study

In this parametric study, lateral load tests were conducted on a full-scale prototype pile embedded of diameter 0.3 m, embedded depth 5 m, and flexural stiffness of 20.2MN/m^2 onto a two-layered soil stratum. The pile properties are listed in Table 2.

Table 2. Properties of the Pile

Description	Value
Pile Diameter (m)	0.3
Pile length (m)	5
Density of pile (kN/m^3)	25
Flexural Stiffness (EI) MN/m^2	20.2

The classification of the pile has been calculated based on IS 2911-Part 1/Section 4 [25] according to which, if L≤2T, the pile is short rigid, and if L≥4T, then the pile is long flexible. Therefore, the pile used in this study has been classified as intermediate in all cases, as shown in Table 3.

Table 3. Values for Classification of the Pile

Case	Embedded length of the pile (m)	*L/D*	*L/T*
+15D to 0D	5	16.67	3.94
-3D	4.4	14.67	3.47
-6D	3.8	12.67	3.00
-9D	3.2	10.67	2.52

The soil stratum has been modelled as field pile tests 9 to 12 presented by Ismael [24]. A slope of 1 V: 1.5 H was introduced onto the strata. The position of the pile was considered a varying parameter with positions on both the embankment and sloping ground. The position of the pile on the embankment was modelled and tested at 15 pile diameters from the crest (+15D). Then, the position was moved towards the crest by decrements of three pile diameters. The position was varied until the pile was situated and tested at nine pile diameters from the crest on the sloping ground (-9D). The positions of the pile are shown in Figure 1.

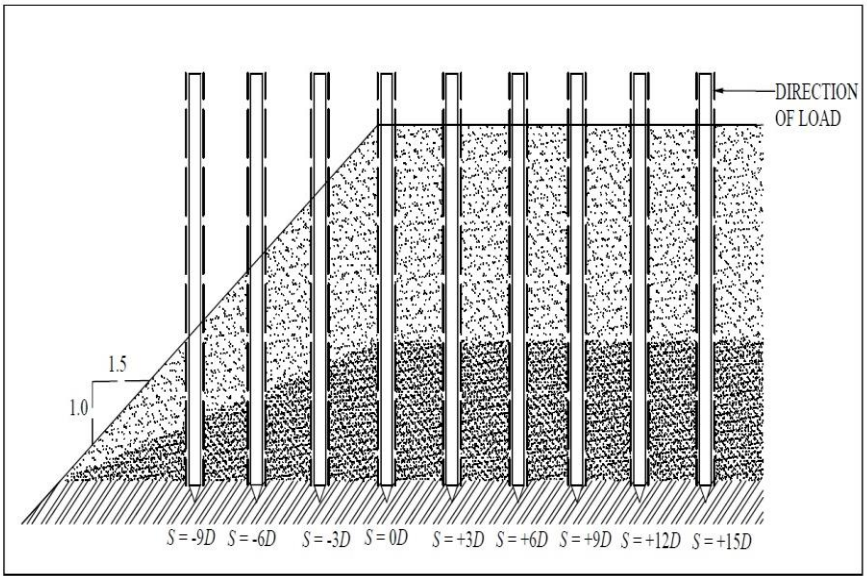

Fig.1. Positions of the pile

The depth of socketing was also considered as a variable parameter with starting from 1D (one time the pile diameter) and further improving it to 2D and 3D. The response of the piles is compared to the corresponding pile tested on undisturbed horizontal ground to estimate the decrease in the lateral load capacity due to the position of the pile. The response is also compared to that of the un-socketed piles tested in identical conditions to estimate the improvement of the lateral load capacity attributed to the rock-socketing. The lateral load corresponding to the pile displacement of 4mm at the ground level was taken as the lateral load capacity of the pile as per IS 14593 – 1998.

4 Validation

Ismael [24] conducted laterally loaded tests on 12 piles, of which piles 9 to 12 are of relevance to the present study. The piles were 5 m long and of 0.3 m in diameter and were situated on two-layered soil strata, a surface layer of cemented sand from 0 to 3.5 m underlain by very dense sand from 3.5 m to 5 m. The average load-deflection response of the four piles was presented and has been considered for comparison of this experimental study.

The full-scale test presented by Ismael [24] was modelled using the model developed on PLAXIS 3D, and the resulting load-deflection curve has been compared with field test results. This is shown in Figure 2. The curves are found to be in good agreement. Therefore, the experimental model is verified to provide results of the lateral response of the pile with acceptable accuracy.

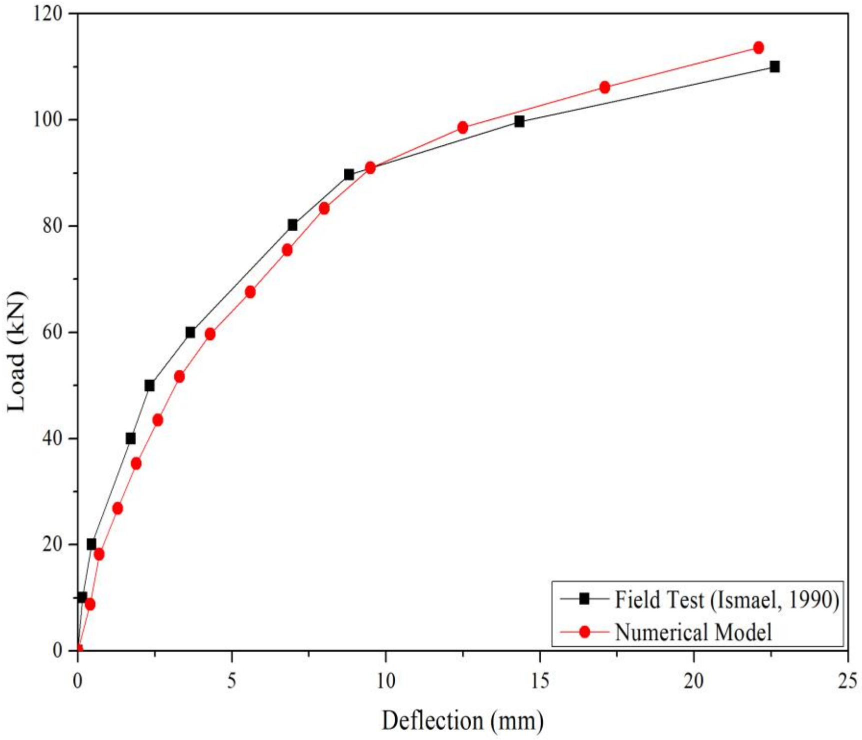

Fig.2. Validation of the numerical model

5 Results and Discussion

In this parametric study, the lateral load corresponding to the pile displacement of 4mm at the ground level was taken as the lateral load capacity of the pile as per IS 14593 – 1998. A test for each case of un-socketed and socketed piles was performed on the undisturbed horizontal ground to observe the ideal response of the pile and estimate the lateral load capacity of the pile to compare to other corresponding cases.

The developed load-displacement curves for the different cases in this study are shown in Figures 3, 4, 5, and 6. The comparison of the observed lateral load capacities for the different piles is shown in figure 7.

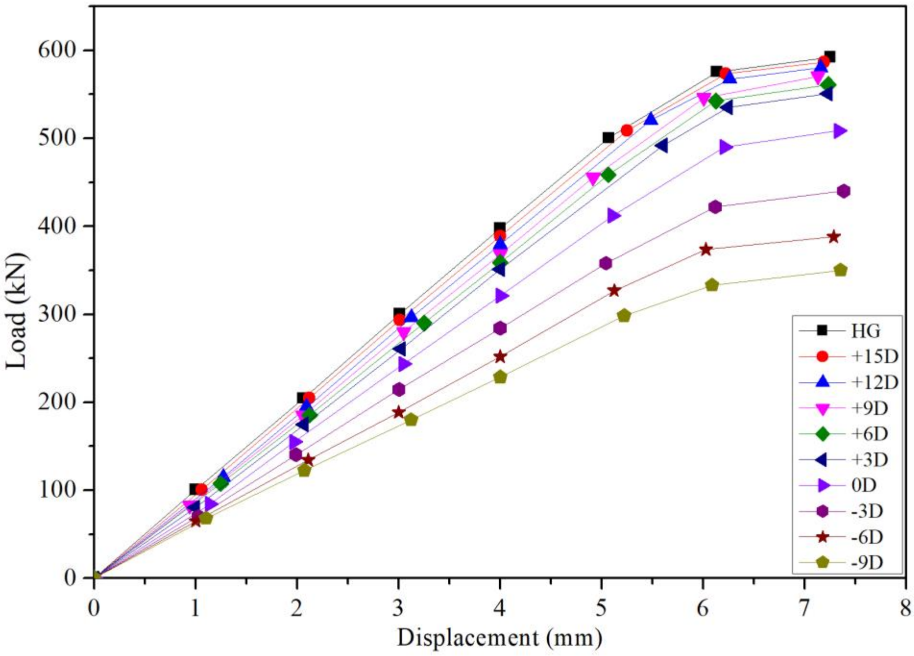

Fig.3. Lateral Load vs. Displacement of un-socketed piles

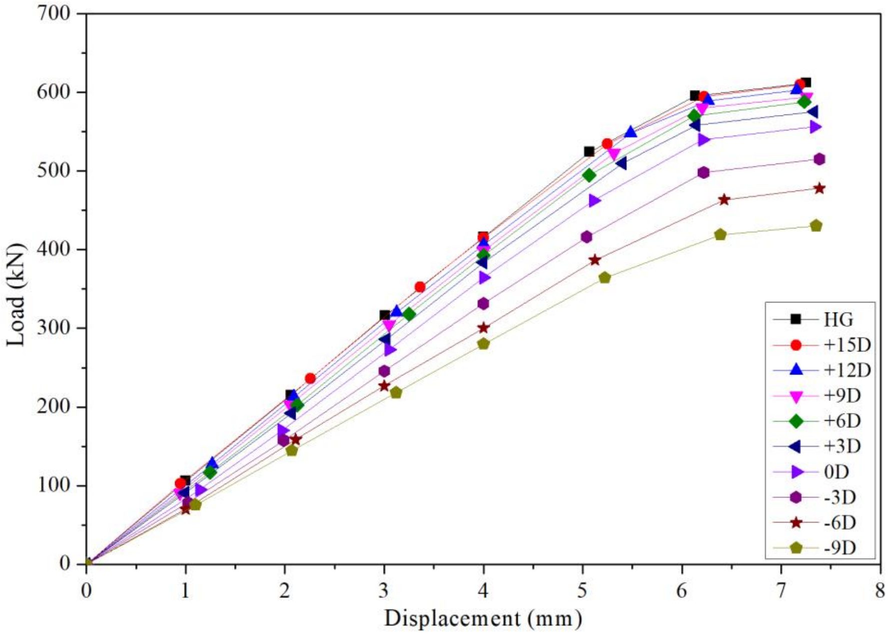

Fig.4. Lateral Load vs. Displacement of 1D socketed piles

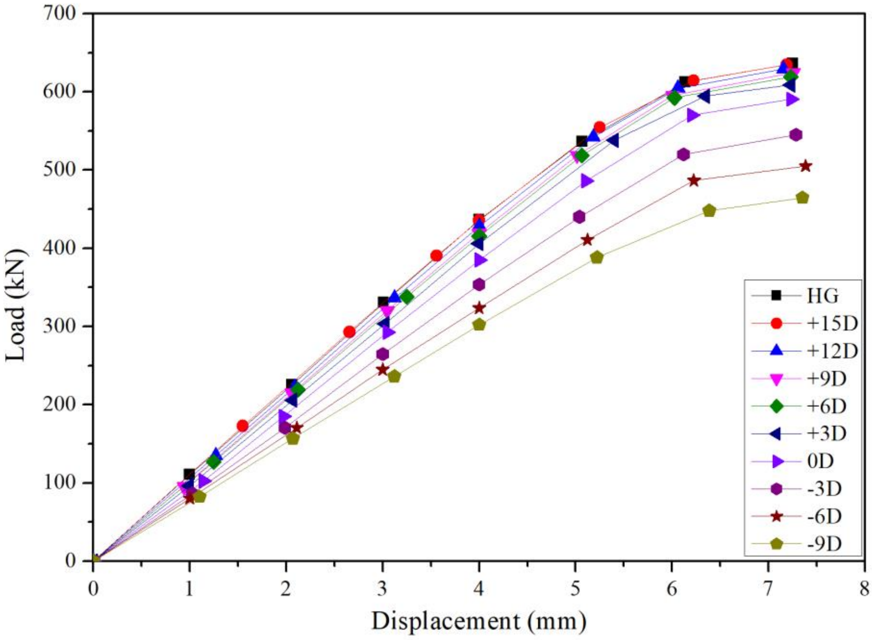

Fig.5. Lateral Load vs. Displacement of 2D socketed piles

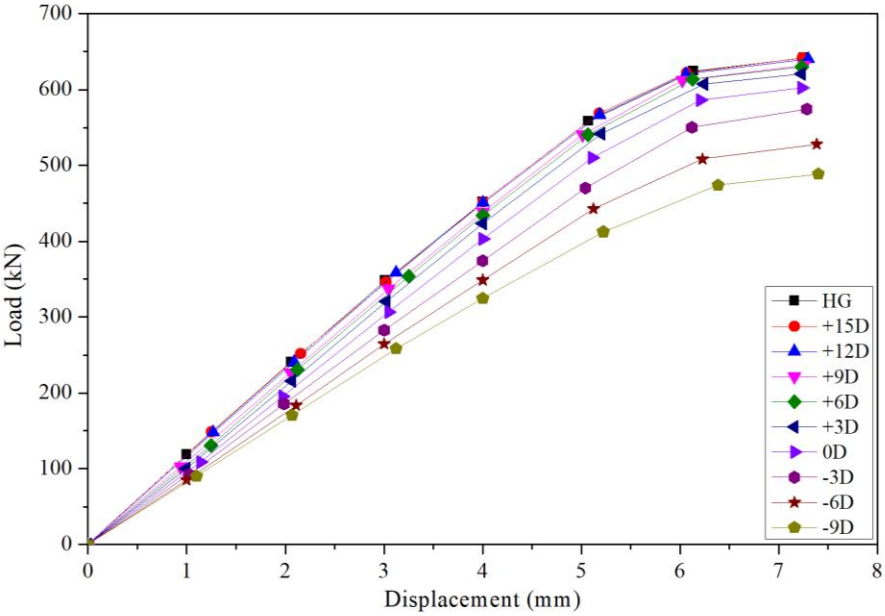

Fig.6. Lateral Load vs. Displacement of 3D socketed piles

From the lateral load-displacement curves, it can be observed that the lateral load capacity decreases as the position of the pile move from the extreme embankment position (+15D) towards the extreme position on the sloping ground (-9D) for both un-socketed and socketed piles. This decrease can be attributed to the effect of edge distance for the piles on the embankment. Further, for the piles situated on the crest and the sloping ground, a reduction of the volume of soil resisting the lateral movement of the pile is another factor.

With the increase in depth of socketing, as the effect of the slope is negated, piles further on the embankment tend to replicate the response of the pile tested on undisturbed horizontal ground. Therefore, it can be observed that the lateral load capacities of the piles on embankment lay closer to the pile on the horizontal ground in the case of 2D and 3D socketing.

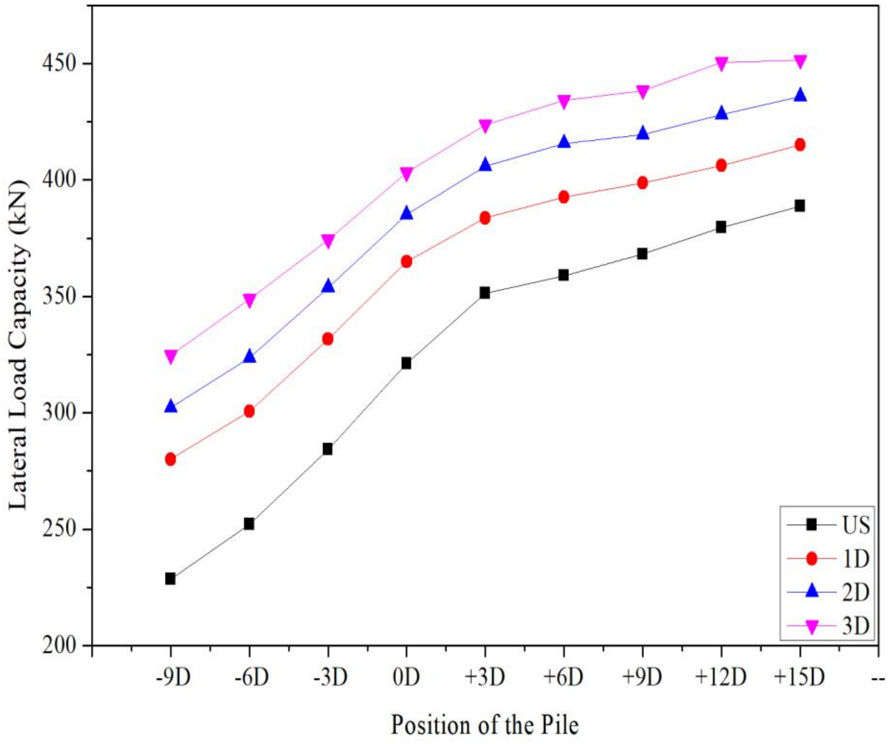

Fig.7. Comparison of Lateral load capacity of all cases

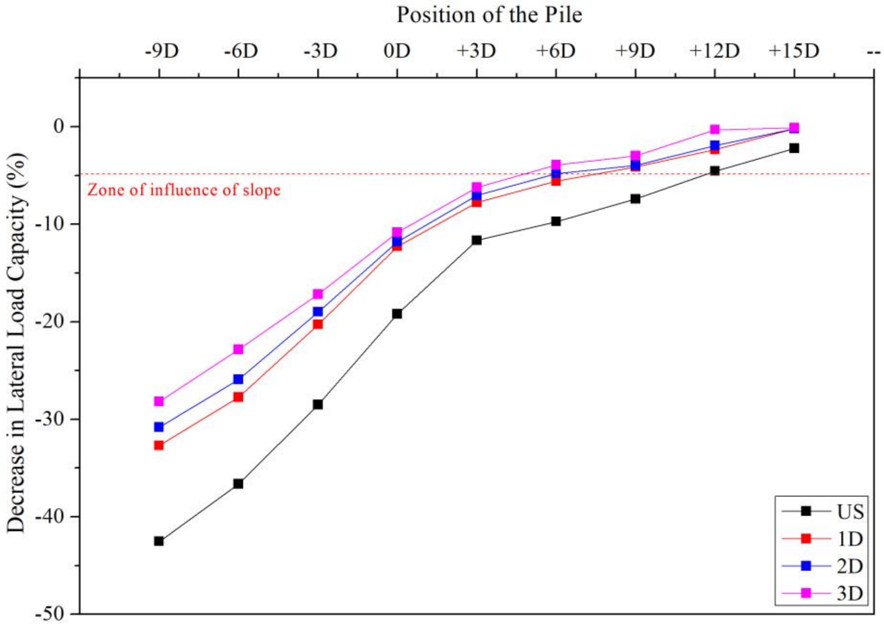

Fig.8. Comparison of Zone of influence of the effect of slope

The increase in lateral load capacity, aided by the effect of rock-socketing, can be observed in Figure 7. The piles situated on the crest and sloping ground can be observed to have the more significant increments in lateral load capacity attributing to the lesser embedded depth causing the load to be transferred onto the rock. Also, it can be observed the increase in lateral load capacity increases with the increase in depth of socketing. In numbers, the lateral load capacity of the pile situated in the extreme position on the sloping ground (-9D) is improved by 22.50%, 32.21%, and 42.05% under 1D, 2D, and 3D socketed conditions, respectively. Whereas, the improvement of lateral load capacity of the pile situated at the extreme embankment position (+15D) is limited to 6.77%, 12.12%, and 16.15% for the corresponding conditions of rock-socketing.

In figure 7, it can be observed that the rate of decrement of lateral load capacity as the position of the piles is moved from extreme embankment position to extreme position on the slope is reduced with the increase in depth of socketing.

It was assuming that a reduction more significant than 5% in the lateral load capacity classifies the pile to be affected by the effect of the slope. Therefore, it implies that the pile is present within the zone of influence. Figure 8 shows the extent of the zone of influence in un-socketed and socketed cases. It can be observed in the figure that the zone of influence of the un-socketed piles (US) lays close to +12D. Further, as rock-socketing was introduced, the zone of influence can be observed to be less than +9D in the case of 1D socketing. The zone of influence further decreases with the increase in depth of socketing to +6D under 2D socketing and lesser than +6D under 3D socketing.

6 Conclusions

This parametric numerical study was focused on studying the effect of rock-socketing to overcome the effect of slope on piles situated in the vicinity of sloping ground on a multi-layered soil. Based on the results of the numerical analyses performed by varying the position of the pile and depth of socketing, the following conclusions were derived,

1. The increment of lateral load capacity increases with an increase in depth of socketing irrespective of the pile position.
2. The effect of rock-socketing is more effective on the piles situated on the crest and the sloping ground as compared to the piles on the embankment. The improvement of the lateral load capacity of the pile situated in the extreme position on the sloping ground (-9D) was 22.50%, 32.21%, and 42.05%. For the pile on the extreme embankment position (+15D), it was 6.77%, 12.12%, and 16.15% under 1D, 2D, and 3D socketed conditions, respectively.
3. The rate of decrement of lateral load capacity as the position of the piles is moved from extreme embankment position to extreme position on the slope is reduced with the increase in depth of socketing.
4. The zone of influence due to the effect of slope decreases with the increase in depth of socketing. The zone of influence lays close to +12D for un-socketed piles. The zone decreases to less +9D in 1D socketing, at +6D in 2D socketing, and lesser than +6D under the 3D depth of socketing.

References

1. Reese, L.C., and Matlock, H., Non-dimensional solutions for laterally-loaded piles with soil modulus assumed proportional to depth. Proceedings of the 8th Texas Conference on Soil Mechanics and Foundation Engineering, Austin, Texas, pp.1-41, (1956).
2. Hetenyi, M. Beams on elastic foundation. The University of Michigan Press, Ann Arbor, Michigan. (1946).
3. Broms, B. B., Lateral resistance of piles in cohesion-less soils. Journal of Soils and Foundations Division ASCE, 90(2), 27-63, (1964).
4. Davidson, H.L. Laterally loaded drilled pier research, Vol 1: Design methodology, Vol. 2: Research documentation. Final Report by GAI Consultants Inc., to Electric Power Research Institute (EPRI), (1982).
5. Reese L. C. and Van Impe, W. F. Single piles and pile groups under lateral loading. CRC Press (2000).
6. Reese, L. C., Isenhower, W. M., and Wang, S. T. Analysis of design of shallow and deep foundations, Wiley, New York (2006).
7. Mezazigh, S., and Levacher, D. Laterally loaded piles in sand: Slope effect on p-y reaction curves. Canadian Geotechnical Journal., 35(3), 433–441, (1998).
8. Muthukkumaran, K., Sundaravadivelu, R. and Gandhi, S.R., Effect of slope on P-Y curves due to surcharge load. Soils and Foundations 48(3), 361-369, (2008).

9. Begum, N. A. and Muthukkumaran, K. Experimental investigation on single model pile in sloping ground under lateral load. International Journal of Geotechnical Engineering 3(1), 133–146, (2009).
10. Muthukkumaran, K. Effect of slope and loading direction on laterally loaded piles in cohesionless soil. International Journal of Geomechanics ASCE, 14(1), 1-7, (2014).
11. Rathod, D., Muthukkumaran, K., and Thallak, S. G., Experimental Investigation on Behavior of a Laterally Loaded Single Pile Located on Sloping Ground. International Journal of Geomechanics ASCE 19(5), 04019021, (2019).
12. IS 14593-1998, Design and construction of bored cast-in-situ piles founded on rocks – Guidelines. Bureau of Indian Standards, New Delhi.
13. Carter, J. P., and Kulhawy, F. H., Analysis of laterally loaded shafts in rock. Geotechnical Engineering 118(6), 839-855, (1992).
14. Reese, L. C., Analysis of laterally loaded piles in weak rock. Journal of Geotechnical and Geoenvironmental Engineering 123(11), 1010-1017, (1997).
15. Muthukkumaran, K, and Prakash, A.R. Behaviour of laterally loaded socketed pile in multi-layered soil-rock profile. Japanese Geotechnical Society Special Publication 3(2). 51-55. http://doi.org/10.3208/jgssp.v03.i07 , (2016).
16. Nandhagopal, A.R., and Muthukkumaran, K. Forthcoming. Effect of Rock-Socketing on Laterally Loaded Piles Installed in the Proximity of Sloping Ground. International Journal of Geomechanics ASCE, (2020).
17. Desai, C., Appel, G. 3-D analysis of laterally loaded structures. Proceedings of the 2nd International Conference on Numerical Methods in Geomechanics, Blacksburg, pp. 405–418 (1976).
18. Yang, Z., Jeremi, B.: Numerical analysis of pile behaviour under lateral loads in layered elastic–plastic soils. Int. J. Numer. Anal. Methods Geomech. 26(14), 1385–1406, (2002).
19. Chae, K. S., Ugai, K., and Wakai, A. Lateral resistance of short single piles and pile groups located near slopes. International Journal of Geomechanics ASCE, 4(2): 93-103 (2004).
20. Georgiadis, K. and Georgiadis, M. Undrained Lateral Pile Response in Sloping Ground, Journal of Geotechical and Geoenvironmental Engineering, ASCE, 136(11): 1489-1500, (2010).
21. Georgiadis, K. and Georgiadis, M. Development of p-y curves for undrained response of piles near slopes, Computers and Geotechnics, 40: 53-61, (2012).
22. Karthigeyan, S, Ramakrishna V.V.G.S.T. and K. Rajagopal. Behaviour of rock socketed short piles under lateral loads. Proceedings of IGC 2004. 386 – 389, (2004)
23. Karthigeyan, S and Rajagopal, K. Influence of rock-socketing on the lateral response of single pile. Indian Geotechnical Journal 42(1), 49-55, (2012).
24. Ismael, N. Behavior of laterally loaded bored piles in cemented sand. Journal of the Geotechnical Engineering Division, ASCE: 1678–1699, (1990).
25. IS 2911 - Part 1/ Section 4 – 2010, Design and construction of pile foundations – code of practice. Bureau of Indian Standards, New Delhi, (2010).