Numerical Study on the Effect of Slope and Loading Direction on Laterally Loaded Piles in Sand

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Abstract. Piles are subjected to lateral loading due to wind or wave action and earthquakes. Therefore, it is important to understand the pile response under the action of lateral loads. The study of laterally loaded pile response requires a proper assessment of soil-structure interaction phenomenon involving the interaction between the pile and the surrounding soil. The deflection of pile is an important factor to be considered in understanding the behavior of laterally loaded piles. Pile foundations are majorly utilized in coastal regions and are generally susceptible to slopes. Hence, to understand the effect of sloping ground on a laterally loaded pile is a necessity. The lateral loads may act on both directions (in the forward direction of slope and reverse) depending on natural phenomenon. Though, various experimental studies have been done to understand the effect of slope on laterally loaded piles, the effect of loading direction is predominantly not considered.

In this paper, the results of the laboratory model tests performed to study the effect of slope and loading direction on laterally loaded piles installed in cohesion-less soil (Muthukkumaran, 2014) are validated using FEM software PLAXIS 3D. The slope of 1V:1.5H is maintained throughout the experimental set. The relative densities, distance from the crest of slope towards both sides (slope and embankment) and loading direction are variables that are considered. The pile capacity in sloping grounds is compared to that in horizontal ground and the influence of slopes on the pile capacity is also discussed.

Keywords: Laterally loaded piles; Numerical modelling; Plaxis 3D.

1 Introduction

1.1 General

Numerical methods as compared to field tests are an economical way to analyze the response of laterally loaded pile. Several forms of finite element methods have been used for analysis with various approximations to assess the response of piles influenced by lateral loading. The different finite element approaches are the three-dimensional finite element analysis, the plane strain analysis and the axisymmetric finite element analysis. Matlock and Reese (1960) gave a generalized solution in non-dimensional form for the laterally loaded pile for both elastic and rigid behavior assuming soil modulus variation linearly with depth. Broms (1964a, 1964b) developed solutions for the ultimate lateral resistance of a pile assuming the distribution of lateral soil pressure and considering static of the problem. Chen and

Poulos (1993) studied passive pile behavior by using finite element methods. In two dimensional (2D) analyses, group reductions in pile capacities were observed and compared with single pile results. Chow (1996) suggested a numerical solution which piles were modeled with beam elements as suggested by Hetenyi (1941), soil was modeled using subgrade reaction modulus and pile soil interaction was considered according to the theory of elasticity. Chow (1996) compared his proposed solution with two field cases: Esu and D'Elia (1974) and Kalteziotis et. al (1993); one of these cases is for single pile and the other is for pile groups. Pile deflections, pile rotations, bending moment and shear force distributions throughout pile length were evaluated in this study. It was concluded that results show significantly good agreement with the measured values. Kahyaoglu et al. (2009) used three dimensional (3D) finite element analysis program PLAXIS 3D Foundation to investigate single pile and group of free head pile behavior in horizontally deforming soils. Laboratory setup that Poulos et al. (1995) used was modeled three dimensionally and it was concluded that bending moment distributions show pretty good agreement with the measured values. Sawant et al. 2013) investigated the effect of edge distance from crest of the slope using 3D FEM techniques and from the results it was observed that pile top displacement and the bending moment in the pile decreases with the increase in edge distance as expected theoretically. This suggests the utilization of 3D FEM analyses for parametric studies on piles in the proximity of sloping ground.

2 EXPERIMENTAL WORK

2.1 Test Program

The objective of this paper is to validate the results of the experimental model tests performed by Muthukkumaran (2014) to study the effect of slope angle (horizontal ground with 1V:1.5H slope), pile location with respect to the slope crest and loading direction on the lateral pile capacity of piles installed on the slope and embankment build using dry sand. The finite-element analysis based software, Plaxis 3D is used to estimate the load-deflection response of the model pile installed at all positions in the scope of the experimental set.

The numerical analysis was also carried out in a scheme similar to that of the experimental set. Under forward loading, the test on the horizontal ground was performed first, then with the pile placed farthest distance from the crest of the slope on the embankment and followed by the rest of the positions moving towards the farthest distance from the crest of the slope on the sloping side. The same set of experiments with the exception of the pile on horizontal ground was performed under reverse loading.

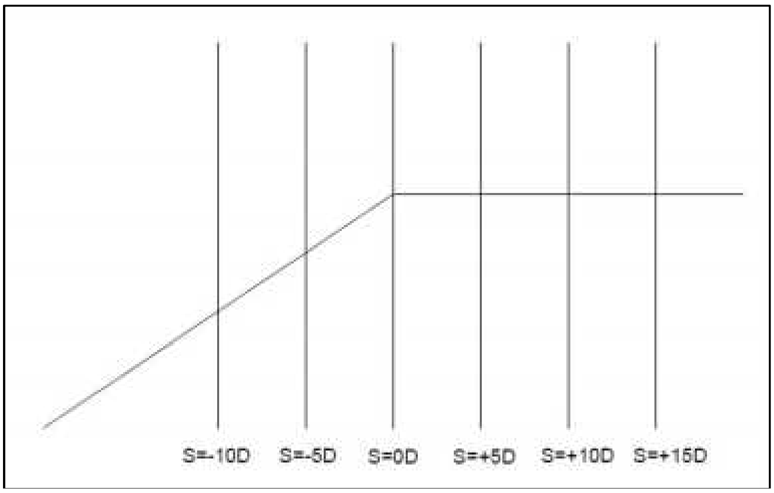

Fig 1. Position of pile with respect to the crest of the slope

3 MODEL STUDY

3.1 Comparison of PLAXIS 3D Models

Numerical models involving FEM offers various approximation methods to predict true response of the laterally loaded piles. The accuracy of these approximations depends on the modeler's ability to replicate the exact scenario as on the field or laboratory. Often the problem being modeled is complex and has to be simplified to obtain an accurate solution. Two of the major factors that have a major impact on both the real and model piles are; (1) the constitutive properties of the sand and (2) the soil–structure interaction at the interface over the structural surface. The finite element modeling and analysis have been carried out using a software package, PLAXIS 3D FOUNDATION, a finite element code for soil and rock analyses, a special tool for solving geotechnical engineering problems. PLAXIS has four different models, namely, Mohr – Coulomb model (MC), Hardening – Soil model (HS), Soft – Soil model (SS) and Soft – Soil – Creep model (SSC) to model different kinds of soil behavior.

Both Hardening – Soil model (HS) and Soft – Soil – Creep model (SSC) do not account for softening due to soil dilatancy and de-bonding effects. These are isotropic hardening models so it can neither model hysteretic and cyclic loading nor cyclic mobility. In addition, Soft – Soil – Creep model tends to over predict the range of elastic soil behavior. This is especially the case for excavation problems, including dredging. Also, the Mohr-Coulomb analysis is quick and simple and secondly as the procedure tends to reduce errors, hence the Mohr – Coulomb model is used for the present analysis. The procedure to perform an analysis with PLAXIS 3D FOUNDATION includes the creation of a geometry model, material properties, mesh generation, defining and executing calculation and evaluation of results.

3.2 Material Parameters of Soil

Material properties and model parameters for the soil and pile are entered into the materials tab. The interface characteristics are also specified along with the same by the user. The angle of internal friction, dilatancy angle and Young's modulus for different relative densities are obtained by conducting direct-shear tests. These angles are taken as the reference for other input parameters such as Poisson's ratio for soil as per Zhu (2012). The interface friction is considered as 0.9 under static loading.

The densities of the sand are based on the values obtained by tests performed on the Cauvery river sand collected for the experimental tests. The sand was classified as poorly graded (SP) as per IS 1498.

Table 1: Properties of Sand Bed

S. No	Properties	Units	Loose	Medium	Dense
1	Density of unsaturated soil	kN/m^3	16.56	17.26	18.96
2	Density of saturated soil	kN/m^3	18.68	19.01	20.52
3	Young's Modulus	kPa	10.0E3	30E3	45E3
4	Poisson's Ratio		0.34	0.32	0.31
5	Friction Angle	°	35	37	39
6	Dilatancy Angle	°	5	7	9
7	Interface Reduction Factor		0.9	0.9	0.9

3.3 Material Parameters of Pile

The embedded beam option of PLAXIS 3D was not adopted as it does not take into account the relative displacement between soil and pile in the lateral direction. Therefore, the pile was recreated by adopting the extruded polycurve and plate option as the best alternative with an interface friction factor of 0.9. To carry out this parametric study, the model pile has been recreated as is provided in Muthukkumaran (2014). A simple bending test was performed to estimate the flexural stiffness (EI) of the pile from which the Young's modulus was calculated. The Poisson's ratio was adopted as per the aluminum alloy material.

Table 2. Properties of Pile

S. No	Properties	Value
1	Pile Diameter (mm)	25
2	Pile Length (mm)	700
3	Young's Modulus, E (GPa)	27
4	Poisson's Ratio	0.32

3.4 Mesh Generation

The geometry of the soil-pile model is divided into elements for performing finite element calculations. This composition is called a finite element mesh. The mesh generator requires a general meshing parameter, which represents the average element size. The boundary conditions are taken into account for the automatic generation of the mesh in PLAXIS 3D. A global coarseness is refined. Based on a convergence study on the meshes generated with various global coarseness values, the medium coarse mesh size shows good agreement with the experimental values and hence this mesh size is used for the entire analysis.

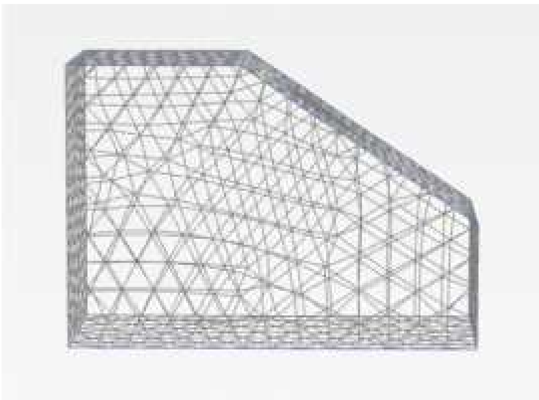

Fig 2. Generated mesh of test tank on Plaxis 3D

3.5 Experimentation

Following the completion of modeling the soil and the pile, the loading was applied using the staged construction on PLAXIS 3D. The required nodes were selected along the ground level to measure the deflection of the pile under the incremental loading as to corroborate the effect of loading as in a pulley system. The pile was allowed to displace little more than the required displacement corresponding to which is the lateral load capacity of the pile (5mm) for better understanding of the load-deflection trend.

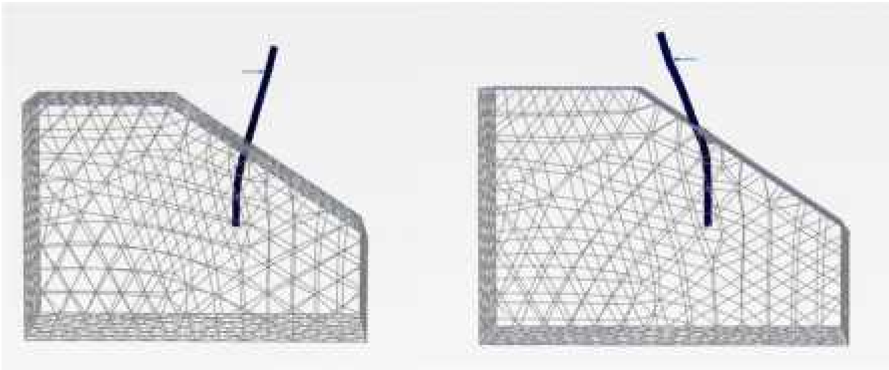

Fig 3. The mesh modified after application of lateral (a) Forward and (b) Reverse loading

4 Results and Discussion

4.1 Piles on Slope

There is a significant decrease in the lateral load capacity of the piles as the ground changes from horizontal to 1V:1.5H slope as seen in the experimental results. The load-deflection curves of the piles placed on the slopes at loose (30%) and medium-dense (45%) and dense (70%) conditions are given in fig.2, 3 and 4.

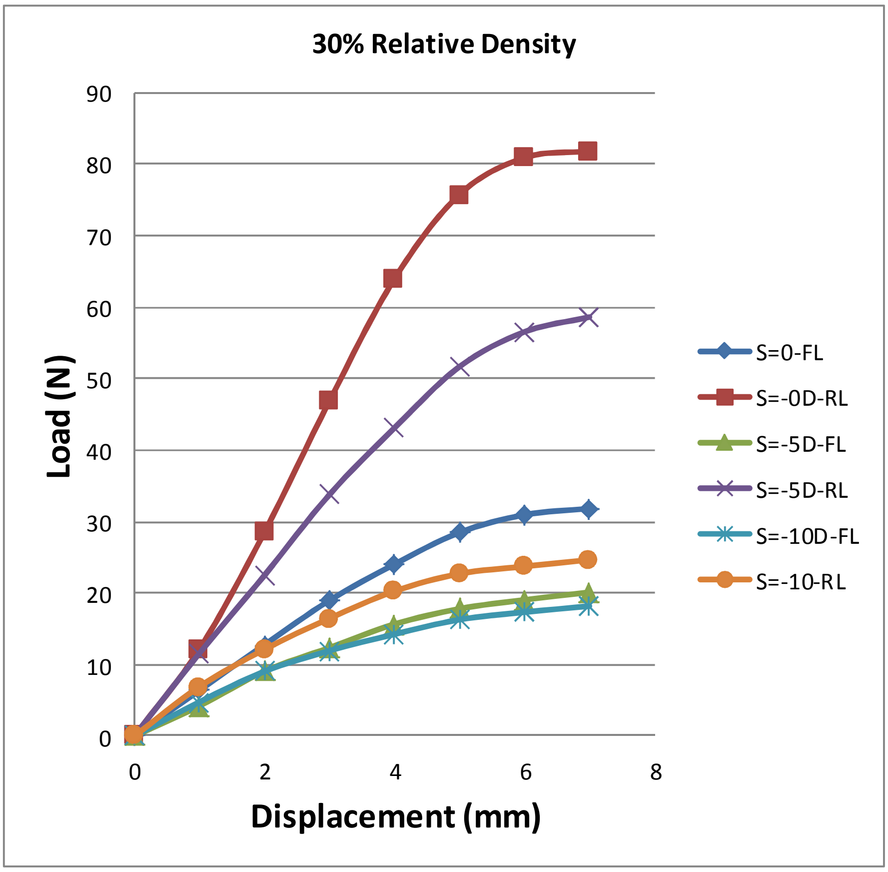

Fig 4. Load-deflection curves for piles on the slope at 30% relative density

The results of the numerical analysis for the piles on slope at 30% relative density, the results are a bit overestimated but are within an acceptable range. The average cumulative difference percentage for both forward and reverse loading cases approximates to 15%. The difference between the values obtained from both approaches is very less at the early displacements and extends gradually increases as the pile displacement increases.

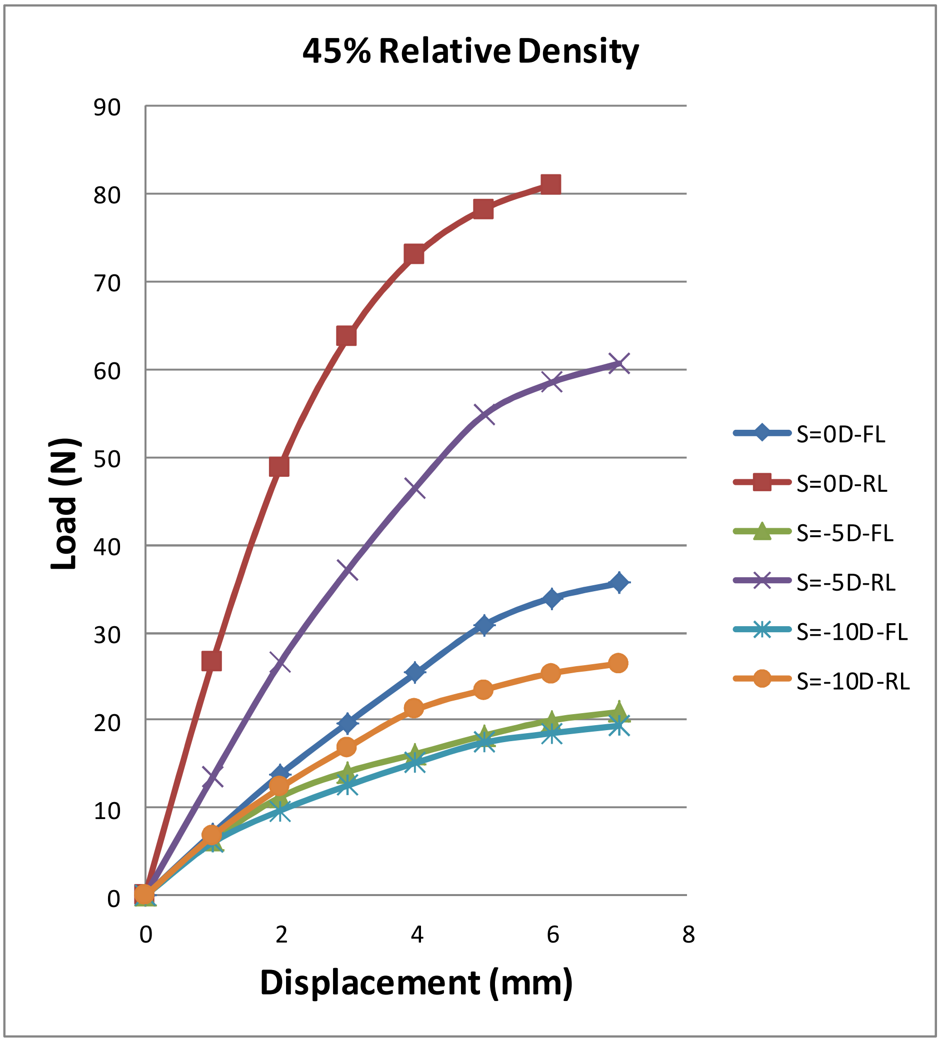

Fig 5. Load-deflection curves for piles on the slope at 45% relative density

Some of the experimental values of lateral load capacity for the piles on slope at medium dense condition are lesser than that of the loose condition whereas, PLAXIS estimates a relative increase in lateral load capacity for the piles in all positions on medium-dense soil when compared to that of loose condition. The average difference between analytical and numerical values cumulative of both forward and reverse loading condtions increases to approximately 25% for medium-dense cases.

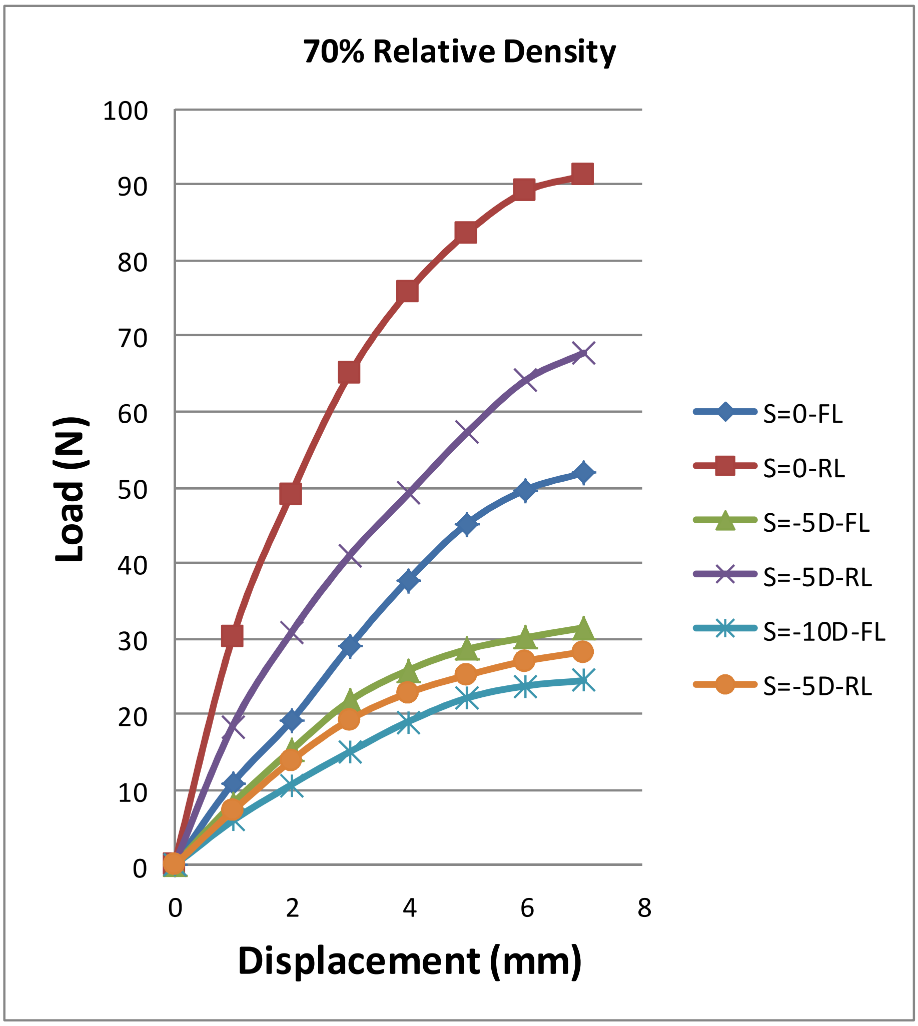

Fig 6. Load-deflection curves for piles on the slope at 70% relative density

In the dense condition, the increase in lateral load capacity is similar for both experimental and numerical values and therefore, the obtained values are quite indifferent to that of 45% relative density. The average difference between the analytical and numerical values of cases under both forward and reverse loading cases remains approximately 25% for the piles on slope on dense state of soil.

From the results, the load-deflection curve of the piles on slope in loose and medium-dense condition under forward loading becomes parallel to the displacement axis beyond 3mm and for piles in dense soil it is parallel beyond 5mm. The results of the numerical analysis are well comparable to that of the experimental tests.

4.2 Piles on Embankment

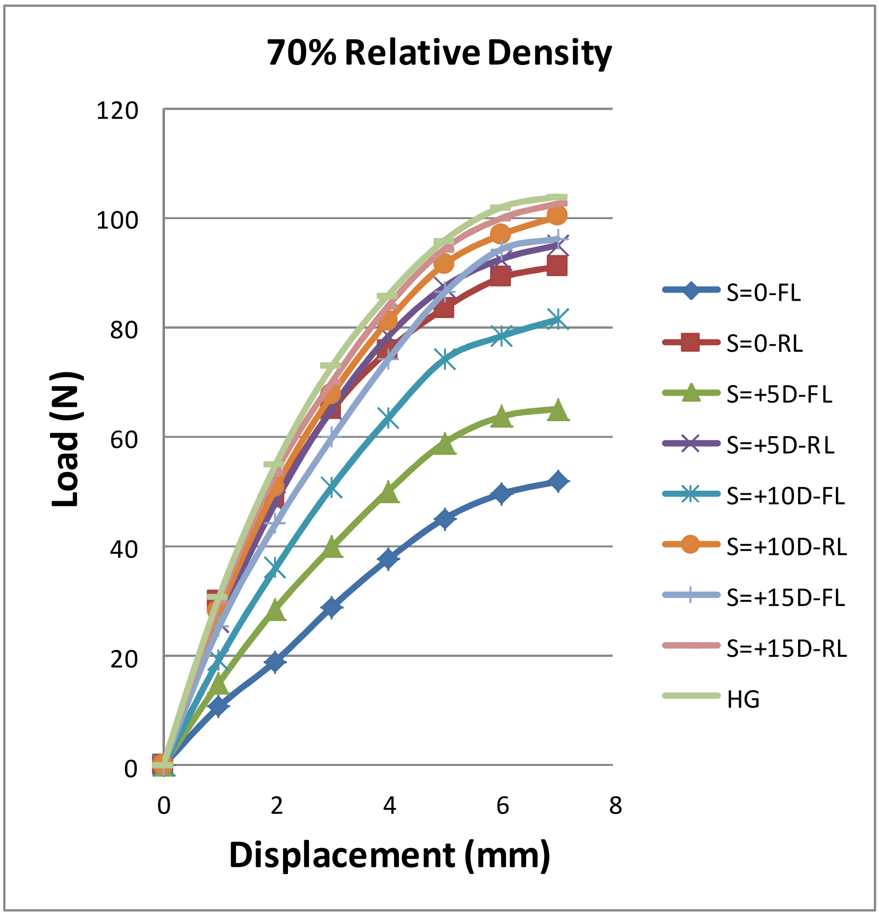

Fig.7. Load-deflection curves for piles on the embankment at 70% relative density

The lateral load capacity of the piles on embankment which is generally in dense condition is estimated by numerical analysis and experimental analysis. The values thus obtained possess marginal differences. The cumulative average difference of the piles on the embankment is less than 15%.

5 Conclusions

- Numerical analysis for the lateral loaded piles within the region affected by the effect of slope is quite efficient and can be used for basic estimation of lateral loads for piles.

- PLAXIS 3D has considerably overestimated the lateral load carrying capacity of the pile in almost all cases. The numerically estimated values are closer to the expected values in cases of the piles on embankment than the piles on the sloping ground.
- PLAXIS 3D has considered the relative stiffness of soil-pile interaction of piles installed in the vicinity of sloping grounds in case of cohesionless soil under static lateral loading with a good approximation.

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