Study of the Effect of Slope, Location and Loading Direction of Single Pile on the Lateral Load Capacity

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Abstract. Berthing structures are one of the main facilities constructed in ports, which mainly interact with the incoming vessels while berthing mooring and repairing. The berthing structure and breakwaters constitute most expensive structure in any ports. Soil found in the coastal region is mainly of soft marine clay which is having low shear strength due to consolidation. Hence pile foundation are mostly adopted for the construction of heavy structures in such soil conditions. Most of the coastline surfaces are sloped in nature and the vertical piles are often subjected to lateral loads in addition to axial loads. Soil structure interaction has to be considered as a dominant factor when structure is built on weak soils.

In this paper, soil structure interaction of single pile located in a berthing structure was studied numerically with PLAXIS 3D software. The response of pile was analyzed by considering various factors such as magnitude of lateral load, behavior of ground and sloping surfaces, position of piles, loading direction. In single pile analysis, pile lateral capacity of ground surface and sloping surfaces was compared. It is observed that lateral capacity decreases when surface changes from horizontal to slope.

Keywords: Berthing structure, Soil structure interaction, PLAXIS 3D, Lateral loads, Pile position, Sloping surfaces

1 Introduction

Water transportation has generally been the most convenient and least expensive mode of transporting goods. Land and sea transportation are linked through port systems and these major and minor ports located along the coastline play an important role in enhancing commercial and industrial activities. Port developments and its activities are directly linked to the overall development of nation since more than 70% of the total trade of our country is via water. Due to the rapid growth in maritime trade demands not only the construction of more ports but also the expansion and development of existing port structures.

Berthing structures are integral part of port or harbour for berthing and mooring of vessels, loading and unloading of cargo and for embarking and disembarking of passengers and vehicles. In berthing structures, lateral loads caused by impact of berthing of vessels, seismic loads, earth pressure, dredging, pressure of wave are considered along with axial forces which are generated mainly due to self-weight of structure and external live loads. Mainly berthing structures can be classified in to two, one is open type structure and another one is vertical face type structure. In open type structure, a rigid deck is supported on vertical pile or combination of vertical and raker piles whereas sheet pile walls, block walls and caisson walls are used in vertical type structures. The berthing structure is subjected to various kinds of loads. If not properly designed, the structure may fail due to these loads. Hence, the study of berthing structure subjected to various loads is necessary to check the adequacy of the structure.

The mutual interaction of structure and surrounding soil is studied under soil structure interaction (SSI). Soil-structure interaction is the process through which the soil's response influences the structure's motion, and the structure's motion influences the soil's response. It gives the influence of the behaviour of soil in the structural response and vice versa. For heavy structures resting on relatively soft soils, ignoring the impacts of soil structure interaction is not a good idea. Most of the coastal structures such as berthing structure, bridge abutment are heavily concreted structures which are founded on piles on week soils. In some constructions, such as offshore structures, retaining walls, bridges, and transmission towers, piles are designed to handle not only axial but also lateral loads. The soil in coastal areas is generally soft clay or loose sand, and the majority of the coastlines have sloping ground surfaces. Piles built on slopes must withstand not only axial loads, but also lateral loads caused by the superstructure. In most cases, the maximum deflection and moment of the piles, rather than its ultimate capacity, is the dominating factor in designing pile foundations to resist lateral loads. For the proper design of pile foundations that support lateral loads, the maximum deflection at the pile head and the distribution of the bending moment along the pile are important sources of information. The behaviour of piles placed on sloping ground differs from piles placed in horizontal ground under lateral loads, resulting in a reduction in pile carrying capacity. The reduction is mostly governed by the reduction of soil mass around the pile and the pile's fixity state. This paper is an effort to study the soil structure interaction of piles in a berthing structure.

2 Literature Review

Kavitha et al., (2016) reviewed the soil–structure interaction analysis of laterally loaded piles. A detailed literature survey was done and analysis shows that unit weight (c), shear modulus (Es), Poisson’s ratio (μ), shearing resistance angle (u), effective cohesion(c), and angle of dilatancy (ψ) are the main parameters which contribute in soil structure interaction. **Begum & Muthukkumaran (2009)** were carried out a series of laboratory model tests on the instrumented pile on horizontal ground, 1V: 2H slope and 1V: 1.5H slope, with the relative density of sand at 30 percent, 45 percent, and 70 percent and varied embedment length to diameter ratios of 25, 30, and 35. load-deflection and bending moment behaviour. The effect of the ground surface, relative density, and embedment length on the depth of fixity for the cohesionless soil was calculated. **Muthukkumaran, K. (2014)** carried out a laboratory model test to study the effect of slope, loading direction (both forward and reverse) and the position of pile on laterally loaded piles in cohesionless soil. It is observed that when ground surface changes from horizontal to sloping surface, the lateral load capacity get reduced. **Sawant & Shukla (2014)** done a three-dimensional finite element analysis to investigate the effect of edge distance from the slope crest of a laterally loaded pile implanted in the sloping ground for different slope angles and pile lengths. The results demonstrate that as the edge distance increases, the pile top displacement and bending moment decrease, however they rise as the slope angle increases. **Deendayal (2016)** studied the lateral load-carrying capacity of the pile, load–deflection response of the pile at pile head, effect of slopes and embedment length on pile capacity, and bending-moment profile down the pile shaft were all investigated based on the experimental results. **Chandrasekaran et al., (2010)** conducted static lateral load testing on 1x2, 2x2, 1x4, and 3x3 model pile groups implanted in soft clay. The tests were conducted on piles with length-to-diameter ratios of 15, 30, and 40, and pile diameter spacing of three to nine. On pile-group interaction, the impacts of pile spacing, number of piles, embedment length, and configuration were explored. The experimental investigation investigated group efficiency, critical spacing, and p multipliers. The experimental results were compared to those produced by using the GROUP software. The lateral capacity of piles in the 3x3 group at three diameter spacing is roughly 40% less than that of a single pile, according to research. **Kaur et al.,(2021)** conducted a three-dimensional finite element analysis of laterally loaded pile groups of configurations 1x1, 2x1, and 3x3, embedded in a two-layered soil consisting of soft clay at liquid limit covering dense sand using PLAXIS 3D . Different values of pile length to diameter ratio (L/D) and ratio of clay layer thickness to pile length (h/L) were used in the analysis to examine the effects of variation in pile length (L) and clay layer thickness (h) on lateral capacity and bending moment profile of pile foundations. The obtained results revealed that as the thickness of the clay layer increases, the lateral capacity decreases non-linearly.

3 Numerical Validation Using PLAXIS 3D

Before staring the actual work, a validation was carried out with PLAXIS 3D based on the experimental investigation of a single pile in a sloping clay layer subjected to lateral load (Sivapriya & Gandhi (2012)). A steel tank with dimensions of 1m x 0.6m x 0.45m makes up the experimental setup. Clayey soil collected from Chennai used for the experiment. Pile has a diameter of 16mm and 450mm long. Table 1 shows the required parameters for the analysis.

Table 1: Input Parameters for Validation

Parameter	**Name**	**Clay**	**Pile**
Material Model	Model	Mohr-Coulomb	Linear elastic
Drainage type	Type	Undrained C	-
Young's Modulus	E(kPa)	8025	700000
Unit Weight	γ (KN/m^3)	17.9	27
Poisson's Ratio	μ	0.495	0.21
Cohesive Strength	c (kPa)	30	-
K_0 determination	-	Automatic	Automatic

The linear elastic and perfectly plastic Mohr–Coulomb failure criterion was adopted for the numerical analysis. A soil volume of 1m x 0.6m x 0.45m was created with a slope of 2 horizontal to 1 vertical and the pile was placed at the crest position. The three node embedded pile in PLAXIS-3D was used to model the pile. Load deflection graph was plotted with experimental and numerical results. The percentage variation between experimental and numerical results are shown in Table 2. It can be seen that some error is existing between numerical and experimental results and it is acceptable. Here numerical curve is well agreed with experimental curve and hence it is validated.

Table 2: Percentage Variation between Experimental and Numerical Results

Load (N)	Experimental Deflection (mm)	Numerical Deflection (mm)	% variation
20	0.2	0.28	33.33
50	0.4	0.53	27.96
80	0.6	0.82	30.98
110	1	1.15	13.95
140	1.2	1.32	9.52
170	1.7	1.9	11.11
200	2.8	3.1	10.17
230	4.7	4.93	4.78
260	5.5	5.9	7.02

4 Single Pile Analysis Using PLAXIS 3D

Jetty constructed for Indian Coast Guard in Cochin Port was chosen as the study area and it has a total length of 220m width 15m and depth 55m. A layout of the berthing structure is given in Figure 1.

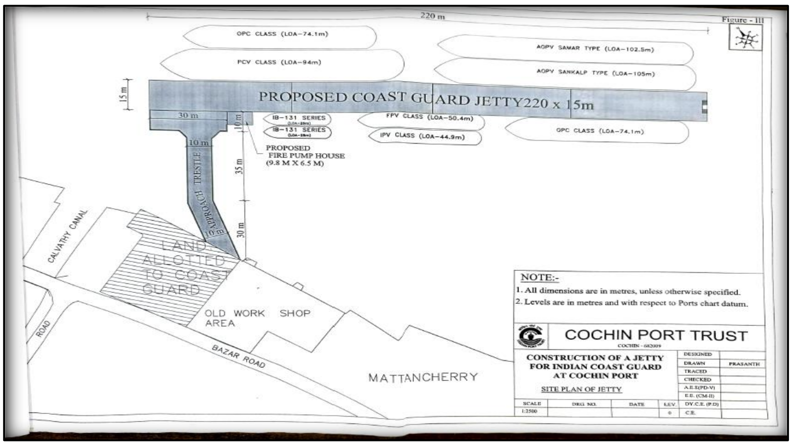

Fig 1: Layout of Berthing Structure

Table 3 shows the different soil layers present in the study area. It's a combination of both cohesive and non-cohesive soils. According to the findings, a soft marine clay subsoil with clayey silt is available up to around -40m and a medium to hard stratum is present below -60m.

Table 3: Different Soil Layers

SL No	Type of Soil	Depth (m)
1	Sandy Clay	0 to -20
2	Clayey Silt	-20 to -30
3	Silty Sand	-30 to -35
4	Sandy Clayey Silt	-35 to -45
5	Clayey Silty Sand	-45 to -50
6	Sandy Silty Clay	-50 to -65

4.1 Analysis of Laterally Loaded Single Pile

This study investigates the behavior of a single pile under horizontal and sloping ground conditions (1V:3H and 1V:5H) by shifting the pile's position relative to the crest position as well as the loading direction. Pile position is taken as S = 0D, 5D, 10D (S- distance from crest position, D- diameter of pile). Figure 3 shows a pictorial representation of sloping surfaces with above mentioned conditions. In the PLAXIS 3D Input window, the model's cross section is created with a dimension of 55m x 50m x 55m and it's shown in Figure 2. Soil layers and structural features are included in the model. The pile is modelled as embedded pile with a diameter of 1m and length 50m. Sloping surface is created with the help of borehole option in the software. The next stage is to assign material and soil parameters to the various structural elements and soil strata after the model has been drawn in the Input window. The Mohr- Coulomb model is used to simulate the behaviour of soil and other materials in this project. Lateral load is applied as point load on the pile top. After that mesh is generated with element distribution of medium size. There are mainly three phases included in staged construction. Soil volume is activated in the initial phase and it is followed by pile activation and finally in the last stage load is activated. Initial phase follows the K_0 procedure whereas all other phases follows plastic as calculation type. The lateral displacement of pile along the direction of lateral load is obtained. The input parameters used in the analysis are presented in Table 4.

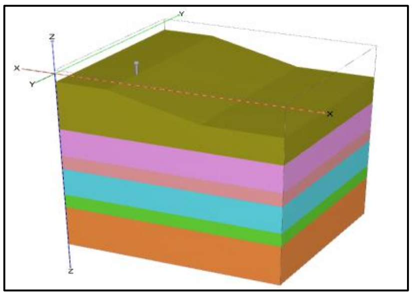

Fig 2: Soil Model

Table 4: Input Parameters for the Present Study

Parameter	Name	Sandy Clay	Clayey Silt	Silty Sand	Sandy Clayey Silt	Clayey Silty Sand	Sandy Silty Clay
Material Model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Drainage type	Type	Undrained B	Undrained A	Undrained B	Undrained B	Undrained B	Undrained A
N Value		4	10	23	32	36	56
Young's Modulus	E(kPa)	6080	4800	8700	23.94e3	42.91e3	69.71e3
Unit Weight	γ (KN/m^3)	18	19	19	18	21	21
Poisson's Ratio	μ	0.35	0.35	0.35	0.3	0.3	0.35
Cohesive Strength	c (kPa)	40	74	147		196	
Angle of Internal friction	φ				32		34

4.2 Load Deflection Curves

The Load-Deflection curves as well as the bending moment variation over the pile's length are shown below. It is clear from the graphs that in the case of horizontal ground surface, the curve for both forward loading and reverse loading is almost same. But when it comes to sloping surface, reverse loading curve lies above the forward loading curve.

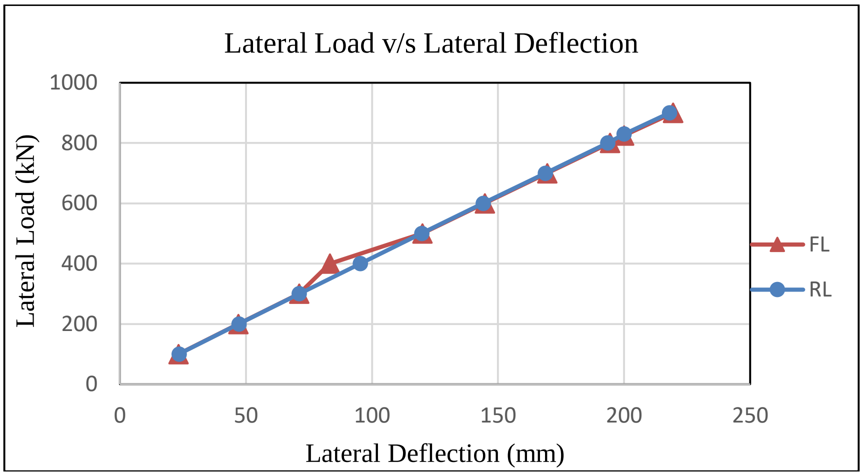

Fig 3: Load Deflection Curve for Ground Surface

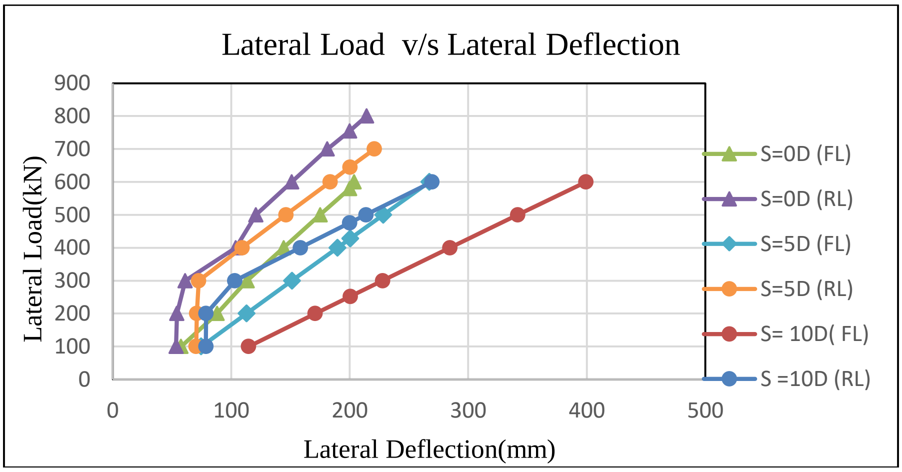

Fig 4: Combined Load Deflection Curves for 1V:3H Slope - Slope Side

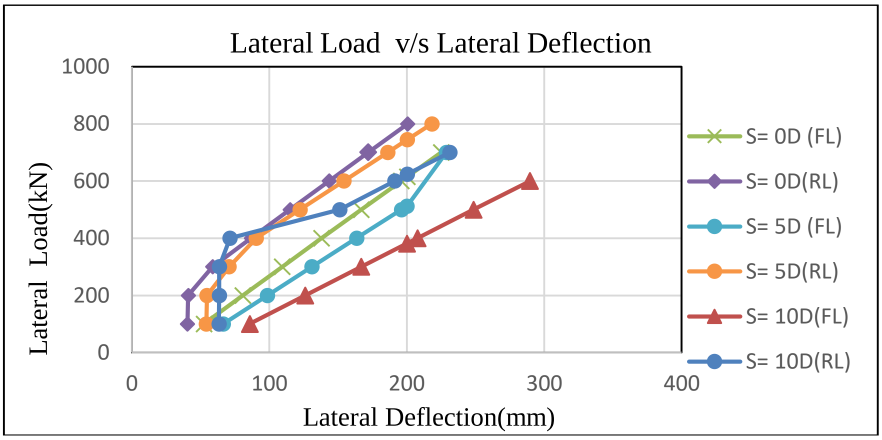

Fig 5: Combined Load Deflection Curve for 1V:5H Slope - Slope Side

The load deflection curve for a 50m long, 1m diameter pile embedded in layered soil beds on a horizontal ground surface, as well as two distinct slopes of 1V:3H and 1V:5H, were plotted and studied (Figures 3 to 5). The load deflection curves are found to be non-linear in all cases. The deflection of the pile top is observed to rise as the bed slope goes from 1:5 to 1:3. This could be owing to the fact that when the bed slope rises, the passive wedge of soil that contributes to pile lateral load resistance decreases significantly. Direction of loading plays an important role in the lateral deflection. Whatever may be the position of pile, loading direction towards the embankment side (reverse loading) results less lateral deflection than forward loading. The above observation is consistent with the result of Muthukkumaran, K. (2014).

According to Rao et al. (1998) and Chandrasekaran et al. (2010), the lateral load was applied until the lateral deflection reaches 20% of the pile diameter at just above the ground surface and the corresponding load was taken as the lateral load capacity of the pile. So in the present study load corresponding to 200mm deflection is taken as the lateral load capacity of the pile. Table 3 shows the lateral load capacity of piles under various circumstances.

Table 5 clearly shows that lateral pile capacity of piles changes with variations in ground surfaces. Horizontal ground surface has more lateral load capacity compared to sloped surfaces. For sloped surfaces, this reduction is due to the reduction in passive resistance able to be mobilized in-front of the piles. The lateral load capacity of the pile is considerably affected by changes in ground surface (horizontal to slope) and loading direction (forward to reverse).A lateral load capacity of 825kN was obtained for pile installed in horizontal ground surface, meanwhile when the ground surface is changed to 1:5 and 1:3, the lateral capacity was reduced to 615kN and 580kN respectively under forward loading. However for reverse loading the capacity drops from 830kN to 800kN, 755kN. Position of pile also plays an important role in the lateral capacity of pile. As the pile go away from the crest position in slope side, lateral capacity get reduced. When the surface changes from ground to 1:3 slope, lateral capacity of pile reduced from 825kN to 580kN, 428kN,252kN for piles placed at S=0D,5D,10D in the slope side under forward loading. When it comes to embankment side, lateral capacity increases with increase in pile distance from the crest position for both forward and reverse loading. The above observation is consistent with the result of Muthukkumaran, K. (2014).

Table 5: Lateral Load Capacity of Piles in Various Conditions (Corresponding to 200 mm Deflection)

		Forward Loading (kN)	Reverse Loading (kN)
Horizontal Ground		825	830
	S= 0D (Crest Position)	580	755
	S=5D (Slope Side)	428	645
1:3 Slope	S=10D (Slope Side)	252	476
	S=5D (Embankment Side)	692	868
	S=10D (Embankment Side)	876	1023
	S=0D (Crest Position)	615	800
	S=5D (Slope Side)	512	745
1:5 Slope	S=10D (Slope Side)	381	624
	S=5D (Embankment Side)	710	863
	S=10D (Embankment Side)	870	1050

4.3 Bending Moment Diagrams

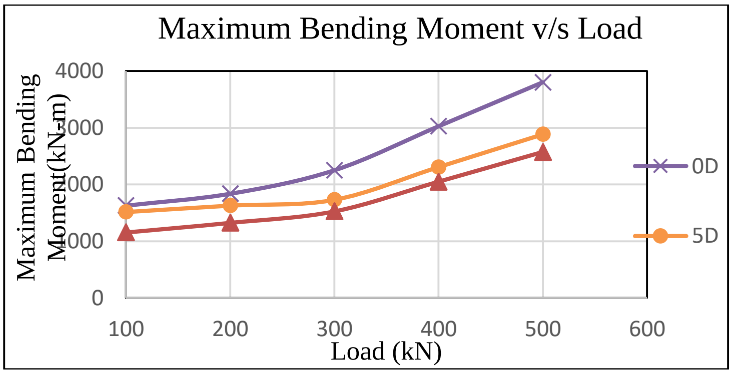

Fig 6: Variation of Maximum Bending Moment with Load When Pile are at Various Positions In 1V:3H Slope

It is clear from Figure 6 that as the load increases the maximum bending moment also increases irrespective of the position of piles. It can be seen that with increasing edge distance, the maximum bending moment in the pile decreases.

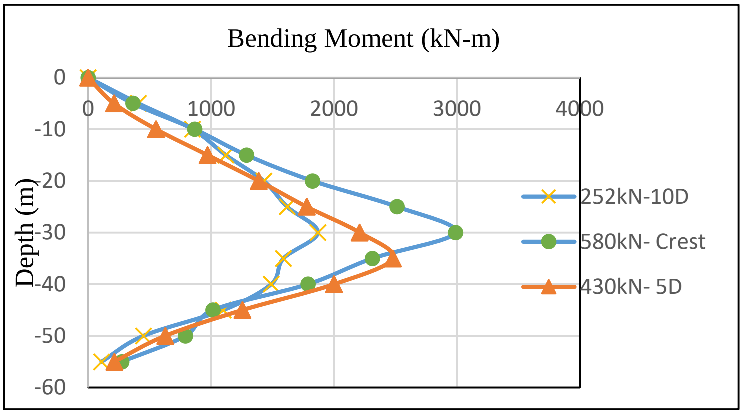

Fig 7: Variation of Bending Moment with Depth for 1V:3H Slope Under Forward Loading

Figure 7 shows the variation of bending moment with depth for a slope of 1V:3H under forward loading. It can be seen that in both conditions bending moment increases with increase in loads. In both cases maximum bending moment is reached at a depth between -25m to -35m.

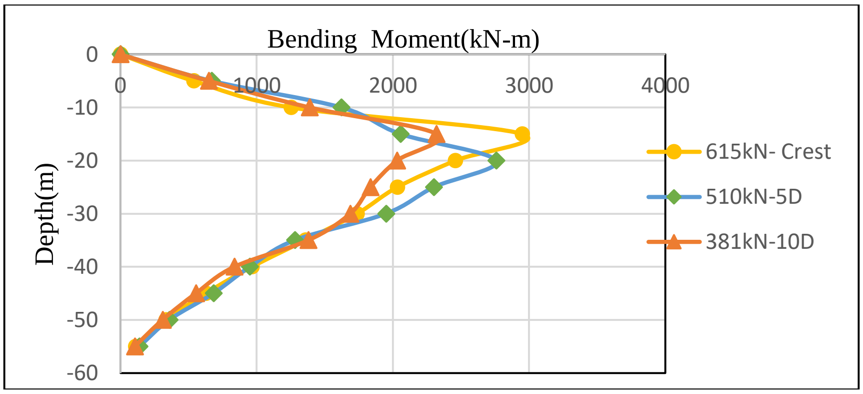

Fig 8: Variation of Bending Moment With Depth for 1V:5H Slope Under Forward Loading.

Figure 8 shows the variation of bending moment with depth for a slope of 1V:5H under forward and reverse loading. It is very clear from the graphs that as load increases the bending moment also increases. Maximum moment is observed between -15m to -25m.

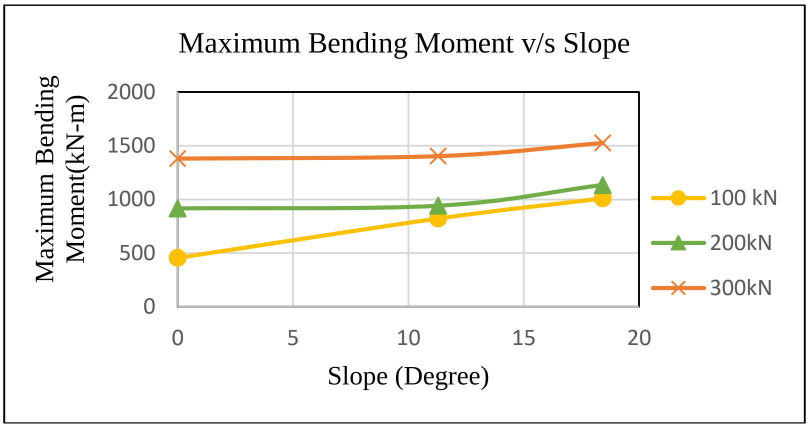

Fig 9: Variation of Maximum Bending Moment with Slope

Variation of Maximum bending moment with slope is shown in Figure 9. When compared to horizontal ground, the maximum bending moment increases as the slope increases. This is because the top portion of the pile has less soil mass, which reduces the mobilization of passive resistance in front of the pile. This result is observed to be in good agreement with Begum & Muthukkumaran (2009) results. Within the same slope, higher load results higher bending

Conclusions

- The deflection of the pile top is observed to rise as the bed slope goes from 1:5 to 1:3. This could be owing to the fact that when the bed slope rises, the passive wedge of soil that contributes to pile lateral load resistance decreases significantly. The above observation is consistent with the result of Sawant, V. A., & Shukla, S. K. (2014).
- When the loading direction changes from forward to reverse direction, deflection value get reduced by 47.67%,45.85% and 73.85% for S=0D,5D,10D respectively for piles placed on 1V:3H slope side, corresponding to 200kN load. Similar pattern is observed in 1V:5H slope surface too.
- It can be seen that the lateral load capacity is more in horizontal ground surface than sloping surfaces. The above observation is consistent with the result of Muthukkumaran, K. (2014). Compared to level ground surface, lateral load capacity is reduced to 34.87% and 29.17% for 1V:3H and 1V:5H respectively under forward loading in L/D ratio of 50. Similarly for reverse loading the reduction is about 9.46% and 3.68% for 1V:3H and 1V:5H respectively.
- Position of pile also plays an important role in the lateral load capacity of pile. As the pile go away from the crest position in slope side, lateral capacity get reduced for both slopes. When pile is placed 10D from the crest, lateral capacity reduced about 78.85% under forward loading for 1:3 slope. However for reverse loading the reduction is about 45.33%.
- The change in loading direction from forward to reverse increases the lateral load capacity by 22.56% and 15.48% for S=5D and S=10D respectively in

embankment side for 1V:3H slope surface. Similarly for 1V:5H surface, the increase in lateral capacity is about 19.45% and 18.75% for S=5D and S=10D respectively. The above observation is consistent with the result of Muthukkumaran, K. (2014).

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