Effect of Slope Angle on Pile Response

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Abstract

Objectives: The present paper aims at finding the influence of soil slope on reduction of horizontal (lateral) load carrying capacity of pile embedded at the crest of clay slope. **Analysis:** 3D finite element analysis has been carried out using PLAXIS 3D. In each analysis, initial stresses developed due to gravity loading are calculated in the first step. In the second step, pile construction is simulated by interchanging the material properties of the appropriate volume elements. Finally, lateral load corresponding to the prescribed horizontal deflection of $0.1D$ at pile top is calculated in last step. **Findings:** The effect of various factors such as slope angle, Length to Diameter ratio of pile and undrained cohesion of soil on horizontal load carrying capacity of pile has been studied. From the study, it is perceived that the load carrying capacity for a prescribed displacement increases with increase in length to diameter ratio and undrained cohesion whereas capacity reduces with increase in slope angle. There is approximately 10% and 27% decrease in the load carrying capacity when the slope angle changes from 0º to 30º and 0º to 55º respectively. For pile having L/D = 10, the deflections are observed throughout the length of the pile where as for pile having L/D = 25, the deflections are extending up to certain depth and after that depth, the deflection is zero. **Applications/Improvement:** Effect of sloping ground condition on pile response is quantified by numerical analysis. Reduction in the ultimate capacity for sloping ground condition is presented for range of parameters. It is possible to predict the pile response for sloping ground condition for a given pile response in horizontal ground and predicted reduction from tables.

Keywords: Cohesion, Lateral Load Capacity, Pile, Prescribed Displacement, Slope Angle

1. Introduction

Pile foundations are used in locations where the use of shallow foundations would lead to unacceptably low factors of safety against shear failure or excessive settlement. In addition to resisting vertical structural loads, the foundation must also resist the lateral loads, which may be caused by earthquakes, wave action, traffic and wind. Typical structure subjected to lateral loads includes bridge abutments, buildings, transmission towers, offshore platforms. The lateral loads placed on the piles are largely transferred to the soil surrounding the pile within a depth equal to 5 to 10 pile diameters[1]. Therefore, the lateral load

carrying capacity of a pile foundation is dependent on both the properties of the pile and the surrounding soil. The resistance of the soil is primarily dependent on the geometry of the soil (i.e., the slope of the soil in the direction of the load) and the properties of the soil.

Different mathematical methods were formulated in the past to analyze lateral load capacity of single piles and pile groups located in level grounds. These mathematical methods include the subgrade reaction method, the elastic continuum method and the finite element method[2]. Key shortcoming of the subgrade reaction method is that soil is idealized as springs and the continuum nature of soil is not taken into account.

As the soil is assumed as ideal elastic continuum[3], in the elastic continuum approach, soil yielding has not been accounted in this method. 3D elastic finite element analysis of lateral loaded structures[4] have been presented using eight noded hexahedral continuum elements and eight noded interface elements. Solutions to this type of problems have also been obtained by using two-dimensional finite analysis[5]. Triangular linear strain elements[6] were employed in the semi-analytical finite element formulation to represent pile and soil domain with a linearly varying soil modulus. Results were summarized in the form of algebraic expression. These expressions were used to estimate maximum bending moment, the ground level deformations and active length of the pile.

Bridges are naturally at a higher elevation than the surrounding terrain because the primary purpose of a bridge is to provide clearance over the underlying road, river, or gorge. As such, it is most often the case that bridge foundations are placed on or near a slope that connects the different elevations. The slope reduces the lateral resistance of the soil, and therefore, of the pile in the direction of the slope. While weak soil adjacent to a pile can be replaced to increase the lateral pile resistance, not much can be done regarding the undesirable effects of the soil slope except to move the pile further away from the crest. Therefore, it is crucial to know the extent to which the lateral strength of a foundation is reduced by the presence of a slope.

Several numerical experiments[7] were performed with a 3D FE model of a laterally loaded pile located at crest of sloping clayey ground. p–y curves were derived from the model. Results show that ground inclination has a major influence on ultimate load p_u, particularly near to the ground surface. On the other hand, ground inclination has negligible influence on initial slope of the p–y curves. Response of flexible piles placed on a sloping ground in cohesionless soil[8] was predicted using 2D Finite Element Analysis. Piles were modelled as plate elements subjected to plane strain analysis and the soil was modeled as fifteen noded triangular elements of Mohr–Coulomb model. When compared to the case of horizontal ground, there is an increase of 29 % maximum BM (Bending Moment) in the pile for the case of pile situated at the crest of 1V:2H slope. To examine the behavior of piles placed at slope crest due to lateral loading under undrained condition, 3D Finite Element Analysis was performed[9]. New p–y curves were proposed based on the obtained results. This criterion takes into account the adhesion of the pile slope interface and inclination of the slope. Study was extended to examine the influence of the location of pile from the crest of a clay slope[10] on the lateral pile behavior. Influence of the slope angle on the behavior of laterally loaded piles[11] had been investigated. Piles were considered to be located at slope crest. The results illustrated that the maximum bending moment and the pile top deflection increase with an increase in slope angle. Study was extended further to examine the influence of location of pile[12] from the crest of the sloping ground for different pile lengths and slope angles. The results indicate a decrease in the bending moment and the pile top displacement with an increase in the edge distance from slope crest. Some studies investigate the effect of fiber orientation on Basalt Fiber Reinforced Polymer composite retrofitted Reinforced Cement Concrete piles subjected to lateral loads[13]. Some researchers have analyzed the behavior of piles embedded in soft clay sloping ground subjected to lateral loads[14].

Numerical modeling is a cost-effective method to examine the response of laterally loaded piles when compared to laboratory or field tests. From the literature review it can be found that only limited finite element studies are available for lateral load analysis of piles located at sloping grounds. The available studies analyzed the behavior of pile by considering a load applied at pile top. But the design of pile foundations is generally based on the limiting deflection criteria. Hence, in the present paper, 3D finite element analysis has been conducted using PLAXIS 3D to examine the effect of slope angle, undrained shear strength and L/D ratio on lateral load carrying capacity of pile embedded at the crest of clayey slope.

2. Numerical Model

The geometry of the problem considered for analysis is shown in Figure 1. By varying, geometrical characteristics (pile length to diameter ratio (L/D), soil properties and slope angle (θ), a series of analyses are performed using PLAXIS 3D. Two L/D ratios (L/D = 10, 25) are considered in the analyses. The soil behavior is modeled as linearly elastic-perfectly plastic Tresca material where as pile is assumed as linear elastic material.
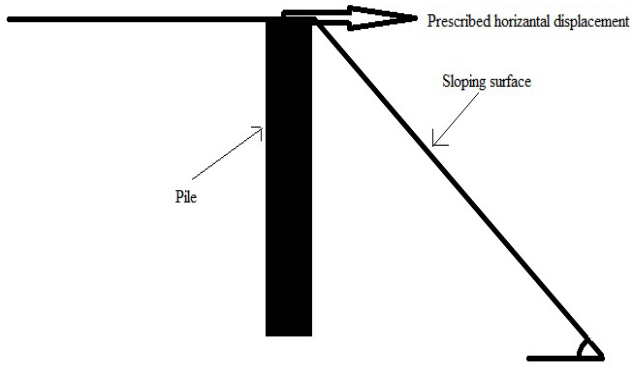
Figure 1. Diametric representation of problem definition.

A typical three dimensional FE mesh is illustrated in Figure 2(a) and its cross-section is represented in Figure 2(b). Fixed boundaries are considered at the distance of 10 times pile diameter (D) from tip/edge of the pile in all directions excluding the sloping surface which is assumed as a free surface. The soil and pile system is taken as an assembly of 10 node tetrahedral elements (Figure 2(c)). The vertical boundaries of the mesh were assumed to be fixed only in the normal direction while the bottom boundary was considered as fixed in all three directions. In each analysis, initial stresses developed due to gravity

loading are calculated in the first step. In the second step, pile is construction is simulated by changing the material properties of the appropriate volume elements. Finally, lateral load corresponding to the prescribed horizontal deflection of $0.1D$ at pile top is calculated in last step.

Hara et al. (1974)[15]developed a relation among undrained shear strength (S_u), shear modulus of soil (G_0) and SPT(N) value. Various empirical relationships between SPT (N) value, shear strength S_u (kg/cm²) and shear modulus of soil G_0 (kg/cm²) are given as:

$$G_0 = 516 S_u^{1.02} \quad (1)$$
$$G_0 = 158N^{0.668} \quad (2)$$
$$S_u = 0.297N^{0.72} \quad (3)$$

The relationship between Shear Modulus G_0 (kg/cm²) and Shear strength S_u (kg/cm²) with the elimination of N-value is given as:

$$G_0 = 487S_u^{0.928} \quad (4)$$

In present paper, Shear Modulus (G_0) is taken as average of value calculated from Equation (1) and Equation (4).

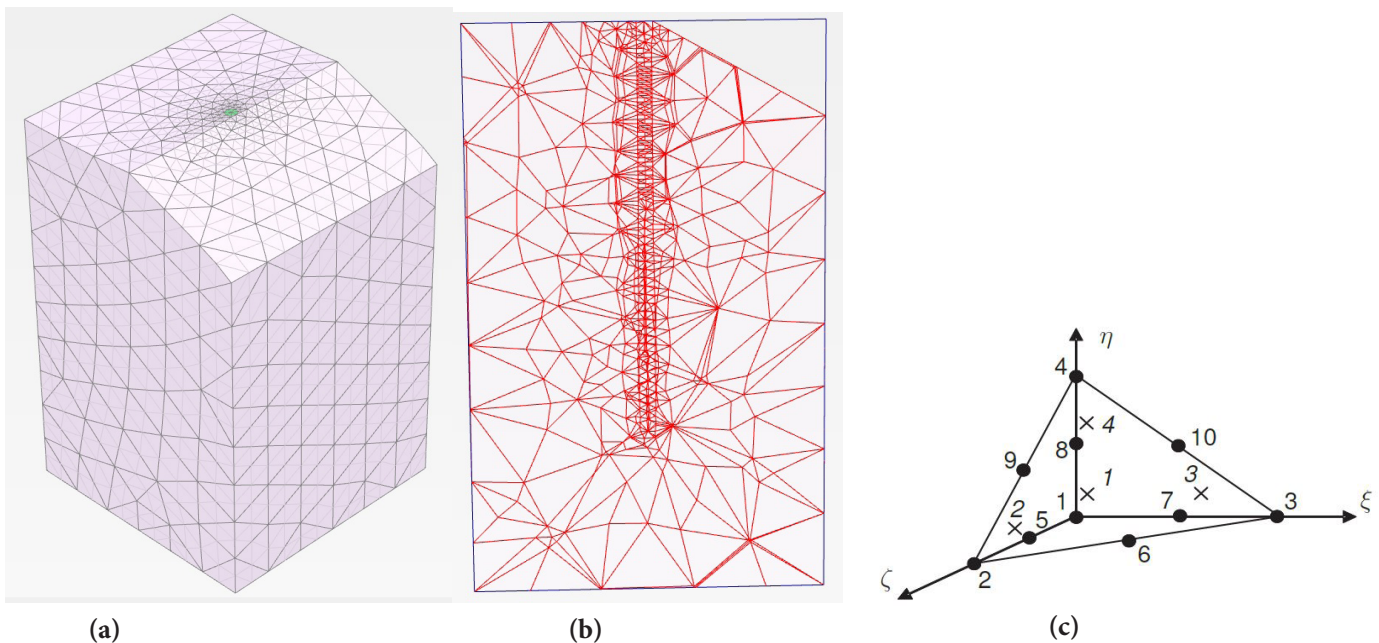Elastic Soil Modulus (E_s) is then calculated as

$$E_s = 2(1+v_s)G_0 \quad (5)$$

Figure 2. **(a)** Isometric view of finite element mesh. **(b)** Vertical cross section view of mesh at pile centre. **(c)** 10 node tetrahedral continuum elements used in meshing the domain.

3. Results and Discussion

Present investigation is aimed at examining the influence of slope angle θ on the lateral load capacity of pile for different values of the modulus of elasticity for soil and pile length-to-diameter (L/D = 10, 25) ratio. The diameter of pile is considered to be 0.6 m, which is kept constant throughout the study. Pile modulus (E_p = 21 GPa) and Poisson's ratio of pile material (v = 0.1) are kept constant. The undrained shear strength of soil is varied between 30 to 100 kPa. These details are reported in Table 1. A prescribed displacement of 10% of pile diameter which is equivalent to 0.06 m has been applied at the pile top. The details various parameters considered to perform nonlinear analyses are presented in Table 1. For the comparison purpose, the pile response is also obtained for level ground.

Table 1. Properties of soil and other parameters considered in the analysis

Parameter	Description	Values
γ_s	Unit weight of soil (kN/m³)	18
L/D	Length to diameter ratio of pile	10,25
θ	Slope angle (degrees)	0,5,10,15,20,25,30,35,40,45,50,55
c	Undrained Shear Strength of soil (kN/m²)	30,40,50,60,70, 80, 90,100
V_s	Poisson's Ratio of soil	0.49

3.1 Effect of Soil Slope

The effect of Soil slope angle θ on lateral load carrying capacity of pile for L/D = 25 and undrained shear strength = 30 kPa is represented in Figure 3. It can be noted that θ=0º refers to the case of pile located in level ground. It can be clearly observed that as slope angle increases the lateral load carrying capacity of pile corresponding to a prescribed

displacement reduces. It can be also observed that there is approximately 10% and 27% decrease in the load carrying capacity when the slope angle changes from 0º to 30º and 0º to 55º respectively. This decrease in the load capacity is due to availability of less passive resistance in case of sloping ground when compared with horizontal ground.

3.2 Effect of L/D Ratio

The load corresponding to 10% pile head displacement is obtained for different values of L/D ratio, undrained cohesion and slope angles. Values of lateral load capacity are tabulated in Table 2 (L/D = 10) and Table 3 (L/D = 25) for comparison. It can be clearly noted that the load carrying capacity increases with increase in L/D ratio of pile. The deflection along the pile lengths for L/D = 25 and 10 is shown in Figure 4(a) and 4(b) respectively. It can be inferred from the figures that for pile having L/D = 10 the deflections are observed throughout the length of the pile where as for pile having L/D = 25, the deflections are extending up to certain depth and after that depth, the deflection is close to zero. The percentage decrease in load carrying capacity of pile due to the presence of slope is almost similar for different L/D ratios.
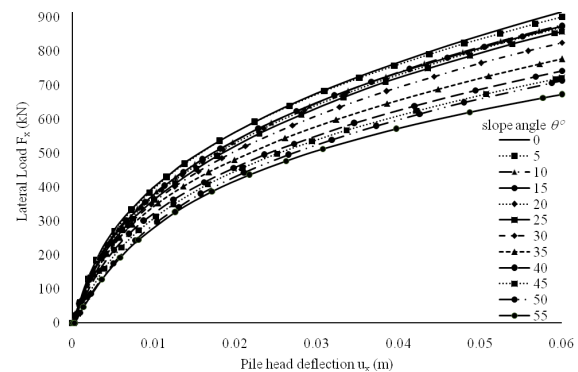

Figure 3. Lateral load vs pile head deflection at different slope angles with L/D =25 and c=30 kPa.

Table 2. Variation in lateral load capacity (kN) with cohesion and slope angle for L/D = 10

c (kPa)	Slope angle θ											
	0	5	10	15	20	25	30	35	40	45	50	55
30	737	728	718	706	680	663	660	636	628	610	580	563
40	918	906	896	882	849	830	828	802	794	776	742	727
50	1083	1067	1056	1040	1002	981	978	950	943	923	884	869
60	1237	1218	1207	1189	1145	1123	1119	1087	1082	1059	1017	1000
70	1384	1362	1350	1332	1282	1257	1254	1218	1214	1189	1142	1123
80	1526	1500	1487	1468	1413	1386	1382	1344	1340	1312	1262	1240
90	1662	1633	1620	1601	1539	1512	1507	1465	1462	1432	1378	1353
100	1795	1762	1749	1729	1662	1633	1628	1582	1580	1548	1490	1463

Table 3. Variation in lateral load capacity (kN) with cohesion and slope angle for $L/D = 25$

c (kPa)	Slope angle θ											
	0	5	10	15	20	25	30	35	40	45	50	55
30	916	902	878	874	871	858	826	778	743	722	713	673
40	1124	1106	1079	1075	1071	1061	1021	967	925	906	900	862
50	1316	1296	1265	1260	1256	1247	1200	1141	1092	1074	1067	1029
60	1497	1476	1440	1435	1428	1421	1368	1304	1246	1232	1222	1184
70	1670	1647	1609	1601	1592	1585	1527	1459	1394	1381	1368	1331
80	1835	1811	1768	1760	1750	1742	1678	1607	1535	1523	1507	1472
90	1995	1970	1922	1914	1901	1894	1823	1749	1671	1660	1640	1607
100	2149	2123	2070	2062	2047	2039	1963	1887	1802	1792	1769	1737
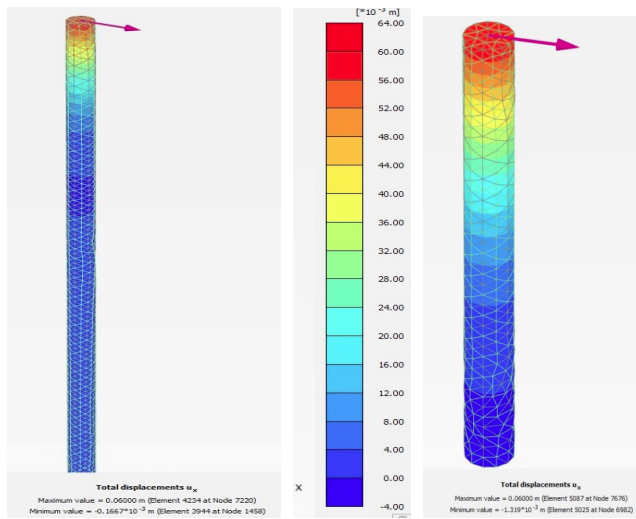
4(a)   4(b)

Figure 4. Distribution of displacement along pile length for. **(a)** $L/D = 25$. **(b)** $L/D = 10$.

Figure 5. Lateral load vs pile head deflection at different slope angles with $L/D = 25$ and $\theta = 30°$.

3.3 Effect of Cohesion

Figure 5 illustrates the typical change in lateral load carrying capacity of pile upto a prescribed pile head displacement of 0.06 m with undrained cohesion for $L/D = 25$ and $\theta = 30°$. It can be clearly observed that for a given L/D ratio and slope angle, as the undrained cohesion increases the load carrying capacity of pile increases. For slope angle $\theta = 30°$ and $L/D = 25$, the increase in cohesion from 30 kPa to 100 kPa increased the lateral pile capacity by approximately 138%. The increase can be attributed to increase in stiffness of soil due to increase in undrained cohesion.
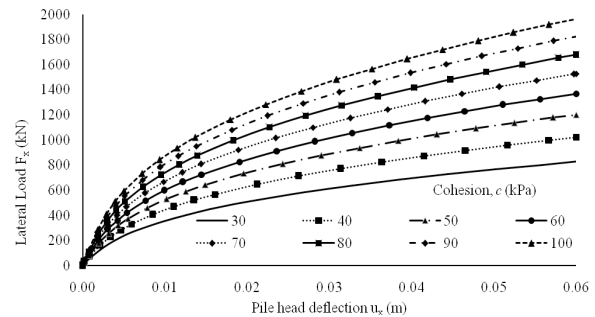
4. Conclusions

From the present study, the following conclusions can be drawn

- Ground slope significantly reduces the horizontal load carrying capacity of pile due to reduction of passive resistance for sloping ground when compared to horizontal ground.
- For a given diameter, increase in embedment length of pile increases the load carrying capacity of pile for a given pile head displacement.
- The load carrying capacity of pile increases with increase in undrained cohesion of surrounding soil due to increase in stiffness of soil with increase in undrained cohesion.

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