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A Numerical Study about the Development of Stressed Zone around Single Pile when Moved away from the Crest of the Slope under Static Lateral Load

Sivapriya S.V[1][0000-0002-9818-1393] and Gandhi S.R[2]

[1] Associate Professor, Department of Civil Engineering, SSN College of Engineering, Chennai – 603110, India.
[2] Professor, NIT- Surat, Gujarat – 395007, India.
sivapriyavijay@gmail.com

Abstract. The presence of pile in natural or man-made slope is a common scenario. The effect of the active pile in a stable slope becomes void when it is moved away to a maximum distance of 5R (R- relative stiffness factor) from the crest of the slope towards the embankment under lateral load. In this paper, a numerical study is made to understand the development of stress zones around the pile when it is kept in a soil slope of 1V:3H; the shear strength is maintained as 30 kPa. A prescribed displacement (5 mm) is applied at the pile head and the lateral load corresponding to it at varied position from the slope crest toward the embankment is studied. The slope effect becomes zero when the lateral load capacity of a single pile at a varied position from the slope crest is equal to the lateral load at horizontal ground. Until zero slope effect, the pile is moved and the stress zone formed around the pile is studied.

Keywords: Active Pile; Stable Slope; Numerical Analysis; Stress Zone; Lateral Load

1 Introduction

The behaviour of laterally loaded pile mainly deals with the soil-structure interaction, which is much more complex in a non- horizontal ground. The need for laterally loaded pile in a sloping ground exists in the area of a man-made embankment of railway track, hoarding board or offshore structures. This slope can be stable or unstable; this study mainly focuses on a stable slope.

The soil-structure interaction of laterally loaded pile in horizontally was initially studied in detail by Reese and Matlock[1] extensively and they proposed equations for deflection, slope, load and moment. Their analytical study remains the basic along with Brom's [2] study. When a pile shows the behaviour of "flexible' it undergoes large deflection before the soil yields, on corollary for 'rigid' piles less importance is given for soil yielding[3]. Due to the development, the structures are constructed in the sloping ground; where the foundation has to be taken to a deeper depth to transfer the load to the soil. The foundation of that particular structures suffers lateral load from waves, wind and also from the soil movement especially when they are located in an off-shore[4]. The governing factors of the laterally loaded pile in the sloping ground are its consistency, shear strength, slope, location of pile etc. With an increase in relative density from 30 to 35% in a slope of 1V:2H, the increase in lateral capacity is 17% and for 1V:1.5H slope it increases by 15% [5].

The effect of slope, when pile moved away from the slope crest is widely studied and inferred. According to Jiang *et al*. [6], when a pile is placed beyond 7D (D- diameter of the pile) from the slope crest the effect of the slope is neglected. Similar to Muthukummaran's [7] study indicates the effect of slope becomes void when it is moved beyond 12 D from slope crest.

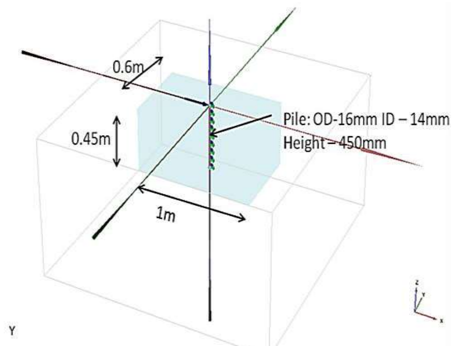
This study mainly deals with the formation of the passive wedge in front of the pile and the slope effect. The study carried out by the authors indicate beyond 2.5 R[8], the effect of slope is not significant; from their study, the formation of passive wedge is inferred.

2 Analysis

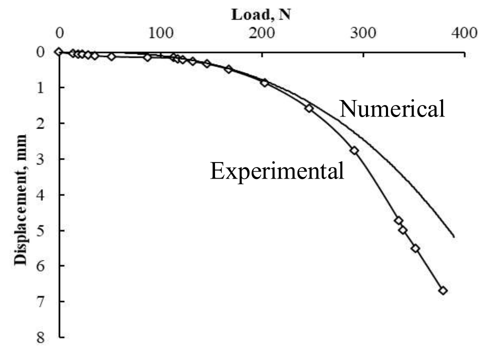
A finite element tool was used in doing the analysis and Table 1 shows the input parameters for the tool. A liner- elastic perfectly plastic soil model proposed by Mohr-Coulomb was used, with 10 node tetrahedral. The embedded pile *in-built* model with outer diameter 16 mm, an inner diameter of 14 mm and length of 450 mm was used and the soil-structure interaction is studied by introducing an interface element such that it did not affect the stiffness properties. The generated model is validated with the experimental work by placing the pile in horizontal ground condition (Fig. 1). The pile was placed in terms of 'R' – stiffness factor from the crest of the slope towards embankment; the value of 'R' was found using the data from the laboratory experiment by having horizontal ground as 94 mm. There are two ways to find the lateral load-bearing capacity of the pile: i. giving the lateral load and finding the displacement or ii. giving prescribed displacement and finding the load. In the current analysis, prescribed displacement of 5 mm (as per IS 2911 part IV,[9]) was given and the stress zone formed around the pile was studied[8],[10].

Table 1. Input Parameters

Element	Parameter	Unit	Variable
Soil	Unit Weight	kN/m^3	17.842
	Young's modulus	kPa	8025
	Poisonn's ratio	-	0.495
	Cohesive strength	kPa	30
Pile	Unit Weight	kN/m^3	27
	Young's modulus	kPa	70,000
	Poisonn's ratio	-	0.2



a. Model Generated



b. Validated with experiment

Fig. 1. Generated model with validation

3 Results and Discussion

The pile located in a stable slope to transfer the lateral load from the structure to the soil - called as an active pile, which is considered in the current study. The lateral capacity of pile increases with an increase in passive resistance offered by the soil to the pile when loaded laterally. This study mainly focuses on a passive wedge - denoted as stress zone formed in front of the pile (Fig. 2). A slope of 1V:3H is formed which starts from the centre of the tank (0.5 m): initially, the pile is kept at the crest of the slope.

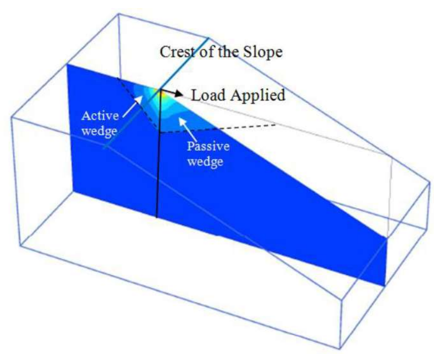


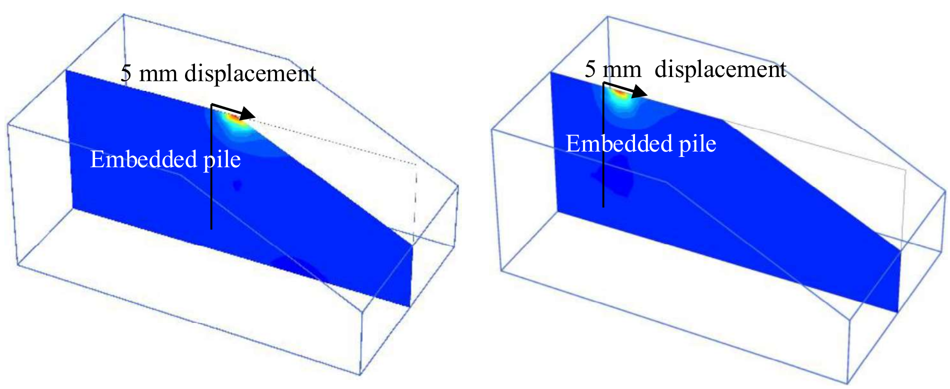
Fig. 2. Formation of wedges in front of the piles

At a point, the length of the passive wedge in lateral direction will not fall in the slope area, the entire formation will happen in the embankment: until that point, the influence of slope exists, beyond which it does not have any significance. The angle of a passive wedge formation and depth at which the deflection of the pile vanishes termed as 'critical depth' is measured (Table 2). The pile was moved away from the crest of the slope at the rate of 1, 2, 2.5, 3, 4, and 5 times 'R'. Beyond 2.5 times the stiffness of the soil (2.5 R), the effect of slope becomes annulled when it moved away from the slope[1], as the wedge formation started falling in the embankment. It is observed by noticing the compressed zone which is the stress zone, formed around the pile. To understand the stress, the soil is bisected at the centre of the pile in the x-axis (Fig. 3).

The passive wedge formed at an angle of 28 degrees for a horizontal ground which got reduced when the pile moved away from the slope till 2.5 R and then increases and reaches the horizontal value passive wedge formation almost at 5R. The depth of critical depth is termed in terms of stiffness factor 'R'. For a horizontal ground, it is 1.22 R, which increases when the pile is placed in a crest of the slope to 1.31 R. This is mainly due to the reduction in passive resistance, which reduces the capacity of the pile. Then after it starts decreasing and reaches the value similar to the horizontal ground at 2.5 R pile position.

Table 2. Measured values

Location of the pile	Angle, deg	Critical depth in terms of R
Horizontal ground	28	1.22
Crest of the slope	26	1.31
1R	25	1.28
2 R	16	1.22
2.5 R	14	1.22
3R	19	1.22
4 R	27	1.22
5 R	28	1.22



a. At crest b. At 5 R

Fig. 3. Stress zones formed around the single pil

4 Conclusions

The single pile is moved away from the crest of the slope and placed at various position in the embankment; prescribed displacement of 5 mm was applied at pile head towards the slope through finite element tool. The following observations are made,

1. The maximum steeper angle of stress zone formed around the pile is observed when the ground condition is horizontal and it became flattered when moved away from the crest of the slope. When the pile is placed at 2.5R location, the stress zone starts to decrease and its length got reduced due to the increase in passive resistance.
2. The critical depth is maximum for pile at the crest and the depth of insertion reduces in that location. The critical depth decreases beyond 2R' location and remains constant.

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