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EFFECT OF SHAPE ON PULLOUT CAPACITY OF RECTANGULAR ANCHOR FOUNDATION EMBEDDED IN SLOPING GROUND

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ABSTRACT

Anchor foundations are required for structures that face uplift forces, such as mooring systems, offshore structures, and structures that undergo lateral forces, such as retaining walls. Over the years, several researchers have investigated the effects of embedment ratio, anchor shape, sloping terrain, adjacentness of anchors to the sloping ground, etc. on the pullout capacity of anchors. However, the shape effects on the pullout capacity of anchors embedded in sloping terrain has not been thoroughly investigated to date. Therefore, in this study, a rigorous three-dimensional (3D) finite element analysis is carried out to investigate the shape effects on the pullout capacity of anchor foundation placed in the sloping ground considering different soil friction angles, angle of sloping terrian, and anchor orientation. The findings of current numerical analyses are initially validated with existing experimental and numerical data, before conducting any extensive parametric study. In each numerical simulation, different sets of parameters are taken into account to determine the pullout capacity of anchors. Numerical results indicate that, the breakout factors of horizontal anchor foundation decrease with the increases of the length-width ratio irrespective of soil strength, sloping angle, and anchor orientation. Further, the variations of shape factor with length-width ratio of the anchor are reported.

Keywords: *Pullout capacity, finite element modeling, shape factor, numerical simulations, breakout factor*

1. INTRODUCTION

Anchor foundations are lightweight structural elements used to withstand the buoyancy of structures such as, mooring systems, offshore structures and structures experiencing lateral forces such as retaining walls etc. Buried pipelines and foundations can also be modelled as soil anchors. Anchor foundations are necessary for the resistance of uplift forces because of horizontal forces above the ground. In the last few decades, numerous researchers have carried out theoretical, experimental, and numerical work to develop a semi-empirical relationship for assessing the load-bearing capacity of anchor foundations in cohesionless soils. In one of the earlier studies Balla (1961) determined the shape of the sliding surfaces for shallow horizontal anchors in dense sand and proposed a rational method to estimate the bearing capacity of the anchors based on the shapes of the sliding surfaces. Prior to this study, other researchers assumed the failure mechanism and suggested evaluating the bearing capacity of the anchor, taking into account the balance of soil mass contained by the failure surface. Horizontal circular, square and rectangular anchors in cohesionless soil were tested using laboratory model by several researchers (Hanna et al., 1972; Das & Seeley, 1975; Rowe, 1978; Murray & Geddes, 1987; Murray & Geddes, 1989; Frydman & Shaham, 1989; Bouazza & Finlay, 1990; Sakai & Tanaka, 1998; Ilamparuthi et al., 2002; Rokonuzzaman & Sakai, 2012). While there are a variety of laboratory tests carried out on horizontal anchors, only a few theoretical and numerical investigations have been performed such as - semi-analytical limit equilibrium analysis method (Meyerhof & Adams, 1968), the cavity expansion method (Vesić, 1971), elastoplastic finite element analysis method (Rowe & Davis, 1982; Vermeer & Sutjiadi, 1985) lower bound limit analysis method (Smith, 1998), - finite element modelling (Islam et al., 2019; Merifield & Sloan, 2006; Merifield et al., 2006). Most of these studies were conducted considering two-dimensional models.

The pullout capacity of anchors in frictional soil is significantly influenced by anchor geometry, length to width ratio (L/B), embedment ratio (H/B), soil friction angle (φ), and soil condition of the site. The pullout capacity of plate anchors in cohesionless soil can be expressed as a function of soil unit weight (γ), area of anchor (A), anchor embedment depth (H) and expressed as follows,

$$Q_u = \gamma N_\gamma A H \tag{1}$$

Where, Q_u denotes the pullout capacity, and N_γ denotes the dimensionless anchor breakout factor. Several researchers Murray & Geddes (1987), Dickin (1988), Frydman & Shaham (1989), Merifield et al. (2006) examined the effect of anchor geometry and shape on the ultimate uplift resistance of anchor. Dickin (1988) investigated that dimensionless anchor breakout factor (Nγ) and failure displacements reduce as the length to width ratio (L/B) increases for rectangular plate anchors. Murray & Geddes (1987) introduced a dimensionless factor named shape factor (S) to conveniently express the impact of length to width ratio on the pullout capacity of rectangular plate anchors. Shape factor can be defined as,

$$Shape\ factor = \frac{Breakout\ factor\ of\ a\ rectangular\ anchor}{Breakout\ factor\ of\ a\ strip\ anchor\ (\frac{L}{B} \geq 10)} \tag{2}$$

Merifield & Sloan (2006), Kumar & Kouzer (2008) and several other researchers investigated that the dimensionless breakout factor increases with an increment in soil friction angle (φ) and anchor embedment ratio (H/B).

Over the years, most studies on anchor foundations have been performed in the horizontal ground. Only a few studies are concerned with the pullout capacity of anchors in or near sloping terrain. Lower bound finite element analysis was carried out by Khuntia & Prasad Sahoo (2018) to determine the uplift reistance of strip anchor close to a slope. Khuntia & Sahoo (2021) also presented a numerical solution to evaluate the vertical uplift resistance of strip anchors embedded in different slope positions in cohesive-frictional soil.

However, the study on the effects of anchor shape on the pullout capacity buried in the sloping ground is rare, especially considering the three-dimensional effect.Therefore, the aim of this study is thus to carry out three-dimensional (3D) finite element model analysis to investigate the shape effect on the pullout capacity of shallow horizontal anchors embedded in purely frictional sloping terrain considering different soil friction angles (φ), angles of sloping terrian ,and anchor orientations.

A typical horizontal rectangular anchor having width B = 1m, thickness, t = 0.05m and length L is embedded at a depth H in a sloping ground where the slope angle is *i*, as shown in figure 1. The boundary of the soil domain is extended to 4H+B in the direction and 4H+L in the direction of anchor length. In case of sloping terrain, the embedment depth H is considered as the depth of anchor midpoint from the slope surface. The anchor is placed 2H from the crest and toe of the slope. To analyse the effect of anchor position along the slope the study comprises two conditions (i.e., anchor width in the direction of the slope, and anchor length in the direction of the slope).

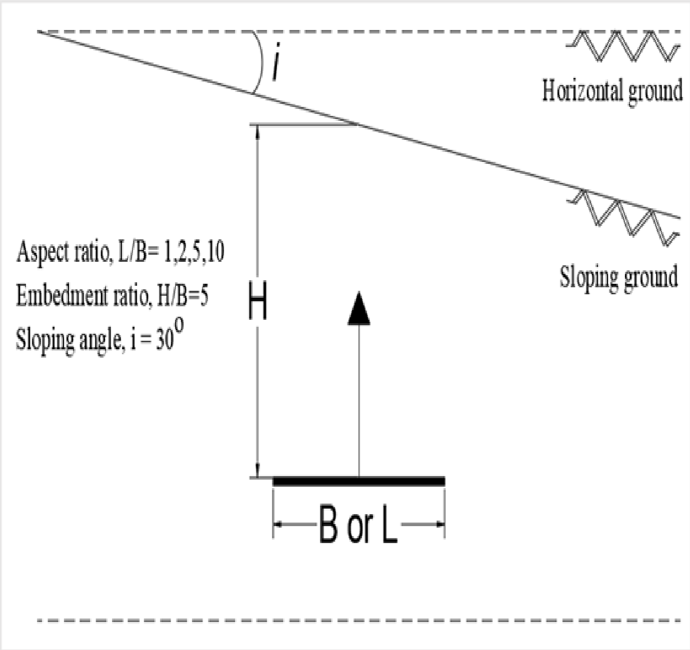


Figure 1(a): Plate anchor model in slope

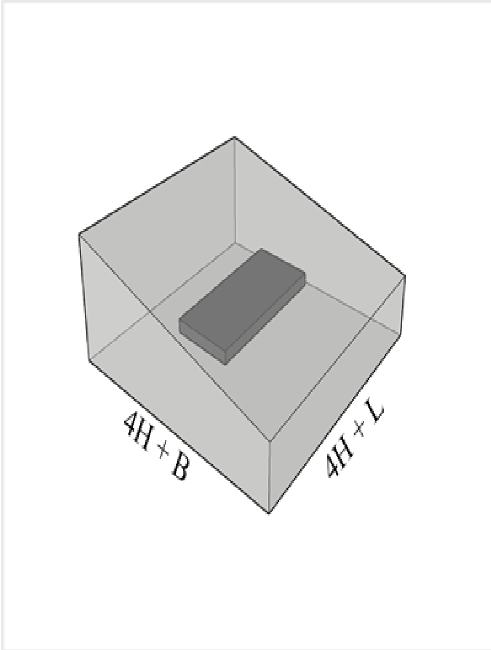


Figure 1(b): 3-D model of plate anchors

2. FINITE ELEMENT ANALYSIS

The model tests were carried out using PLAXIS 3D, a three-dimensional finite element modelling software. The PLAXIS 3D software license was secured through a industrial collaboration with D.ZING. PLAXIS 3D has a variety of soil models for constructing sand models, including the Mohr-Coulomb model, Hardening Soil model, HS Small model, and others. The Hardening Soil model was chosen for this investigation among all of these models. This model accurately illustrates the non-linear behaviour (Dickin & Laman, 2007). The Hardening Soil model correctly depicts the inelastic and stress dependent material behaviour of sand. Anchors were modelled as plate material in the instance of modeling. To neglect the effect of anchor weight on uplift load, anchors were assumed to be weightless. The stiffness of the anchor is regarded extremely high to ensure that it behaves like a rigid plate.

PLAXIS 3D provides fully automated mesh production in various densities, from very coarse to very fine. The influence of mesh density on anchor pullout capacity was investigated using a mesh convergence analysis. The uplift load for 0.2 m displacement of an anchor with a length-width ratio of 5 and an embedment ratio of 3 is shown in Table 1. The uplift load varies significantly with the variation of mesh densities. Very coarse mesh density overestimates the pullout load, whereas very fine mesh density slightly underestimates it.

Table 1: Mesh Convergence Analysis

Mesh density	**No of elements**	**Nodes**	**Pullout Load for 0.2m Displacement (kN)**
Very Coarse	803	1540	3421.37
Coarse	1570	2882	2870.24
Medium	4320	7361	2548.38
Fine	11616	18635	2195.35
Very Fine	30641	46886	1932.8

For the accuracy of results and convenience of study, fine mesh density has been adopted for carrying out the numerical model analysis in this study. A typical mesh having 20682 elements is shown in figure 2. In the calculation mode, a *Pardiso* type solver was employed to estimate the uplift load. On multi-core processors, *Pardiso* is a direct solver that solves the system of equations in parallel. Prior to the start of the calculation, the maximum number of steps and the global tolerance for error were manually set.

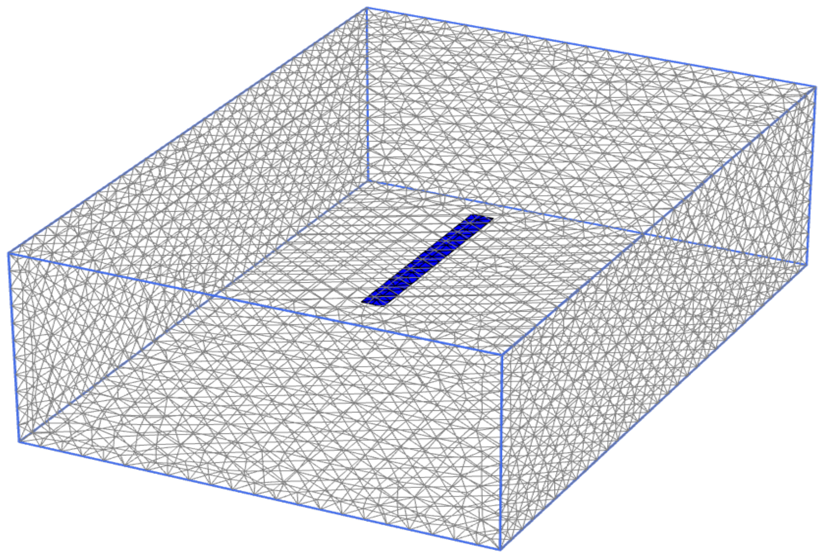
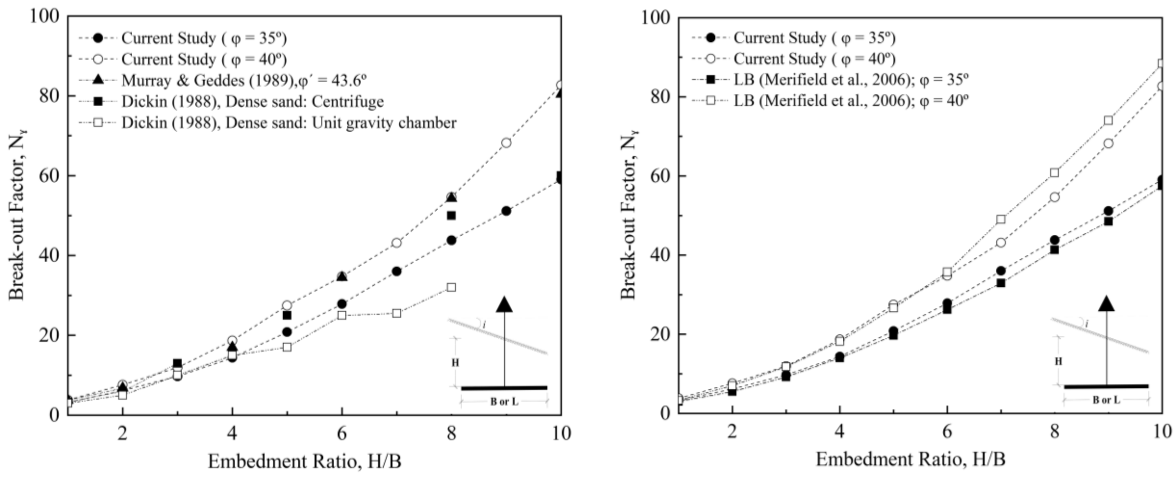


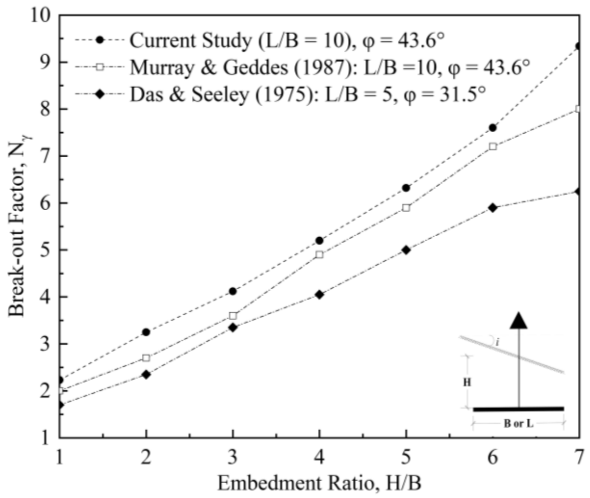
Figure 2: Finite element mesh

3. COMPARISON WITH OTHER EXPERIMENTAL AND NUMERICAL STUDIES

To ensure the accuracy and correctness of present modelling, the numerical results obtained from this study are compared with available established experimental and numerical studies. In case of square anchors, Figure 3(a) depicts a comparison of the current study with experimental results of: (1) centrifuge study (Dickin, 1988), (2) unit gravity chamber study (Dickin, 1988), and (3) laboratory study (Murray & Geddes, 1989). A polished plate with a soil-plate interface angle of 11° was used in the study of Murray & Geddes (1989), and the results approximate quite well with the present study for φ=40°. Up to an embedment ratio (H/B=5), the obtained results are very similar to the centrifuge study of Dickin (1988). However, an apparent discrepancy is observed beyond H/B=4 between the results of unit gravity chamber Dickin (1988) and the present study for φ=35°.



(a) (b)



(c)

Figure 3: Comparison of the present study with (a) experimental results for square anchors (b) numerical results for square anchors, and (c) experimental results for strip anchors

A comparison between the current study and lower bound numerical analysis of Merifield et al. (2006) for both φ=35°, and 40° is shown in figure 3(b). In case of φ=35°, the current study overestimates the results of Merifield et al. (2006) but underestimates for φ=40° when H/B ≥ 6. The reason behind this variation is due to the fact that this study uses a finer mesh density and advanced soil model (i.e., Hardening Soil model).

The results obtained in the present study for strip anchors are compared to the works of Das & Seeley (1975) and Murray & Geddes (1987) in Figure 3(c). The present study overestimates the results of both the studies. This overestimation is because Das & Seeley (1975) considered anchors having L/B=5 are strip anchors and conducted the study in a soil having φ=31.5°, which is different from the present study conditions.

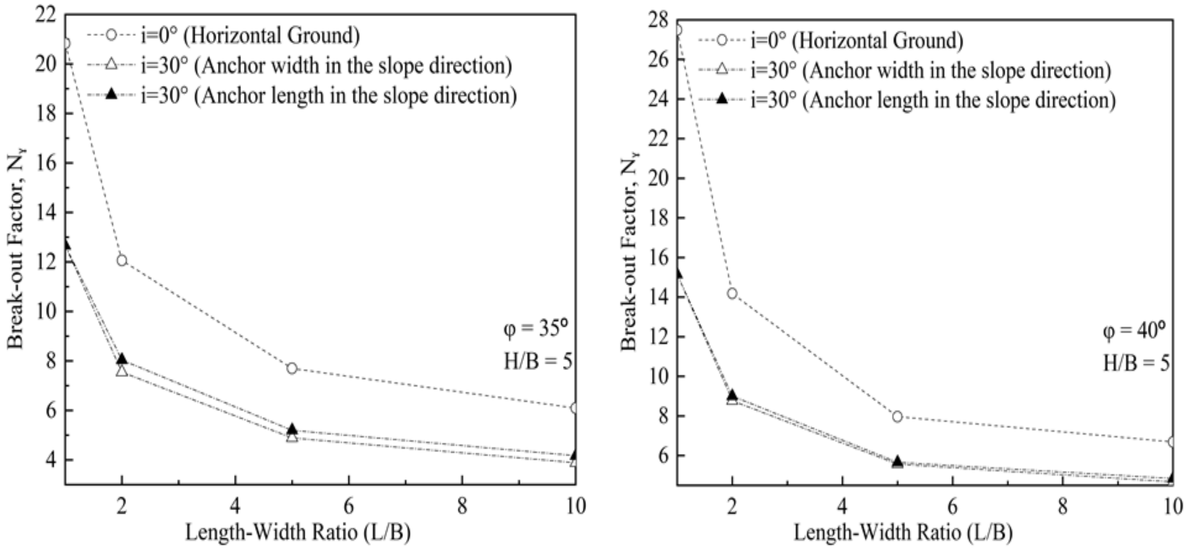
5. PARAMETRIC ANALYSIS

Various aspect ratios (L/B= 1, 2, 5, 10) are adopted to examine the effects of anchor shape on the pullout capacity where L/B= 1 to be a square anchor and L/B= 10 to be a strip anchor (Murray & Geddes, 1987). Anchors of different aspect ratios are embedded at a single embedment depth (i.e., embedment ratio, H/B=5). For parametric studies, two types of cohesionless soils having different unit weights, γ=15 kN/m^3 and 16 kN/m^3 and different friction angles, $\varphi=35^0$ to 40^0 are used to investigate the effect of varying soil strength. The variation of anchor pullout capacity in the presence of a sloping ground is investigated by adopting the angle of slope $i = 30^0$.

6. RESULTS AND DISCUSSION

This study examines the effects of anchor shape on its pullout capacity. PLAXIS-3D model can immediately estimate the ultimate uplift load (Qu) for various numerical analyses. Pullout capacity is expressed as dimensionless breakout factor (N_γ) in this study. Using equation (1), the dimensionless breakout factor (N_γ) was computed.

The dimensionless breakout factor (Nγ) of horizontal plate anchors embedded in the horizontal and sloping ground (i = 30°) at both friction angles is shown in Figures 4 (a) and (b). From Figures 4 (a) and (b) it can be seen that, the breakout factor of anchors decreases as the length-width ratio of anchors increases irrespective of soil strength, sloping angle, and anchor orientation, which agrees with the findings of Murray & Geddes (1987) and Dickin (1988). The equilibrium and limit analysis approaches help explain why there has been a drop in breakout factor and the explanation have been outlined in broad terms by Murray & Geddes (1987).



(a) (b)

Figure 4: Breakout factors of plate anchors embedded in horizontal and sloping ground for (a) φ=35° and (b) φ=40°

The breakout factor at both friction angles decreases significantly when the slope is introduced for all length-width ratios, as shown previously in Figures 4(a) and (b). The change in failure surface area when the anchor is embedded in the slope can be used to the explanation of this reduction. The displacements of anchors in various scenarios are depicted in Figure 5. The failure surface area for a plate anchor embedded in horizontal ground spans a larger area, as shown in figure 5 (a). The failure surface creates approximate angles β_1 = 65° and β_2 = 65°. Figure 5 (b) depicts the failure surface of anchors embedded in sloping ground extending almost vertically to the soil surface on one side, forming an angle of β_1= 100°. In contrast, on the other side, the produced angle is β_2 = 40°, resulting in reduced area coverage by the failure surface.

Moreover, Figures 4 (a) and (b) show that the anchor orientation has little or no impact on anchor breakout factor for lower length-width ratios of anchors (i.e., square anchor). However, for greater length-width ratios, the anchor breakout factor is marginally higher when the anchor length is in the slope direction rather than when the anchor width is in the slope direction. The slight increase is becausewhen an anchor with a higher length-to-width ratio is embedded in a slope, and the length is in the direction of the slope, a longer length is associated with failure. However, when the anchor width is in the slope direction, the situation is reversed. In the latter scenario, the failure surface area is less, as evident in Figures.

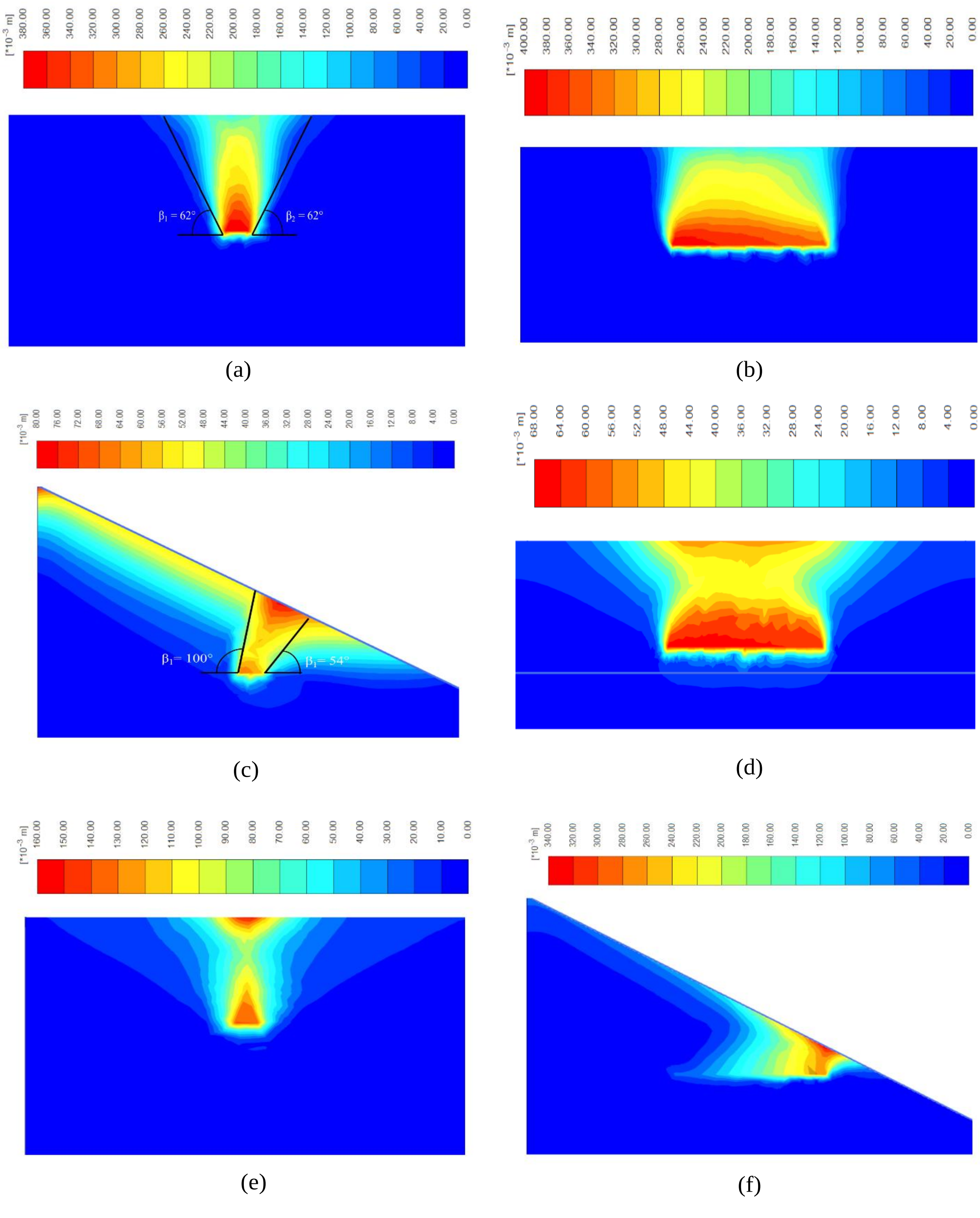
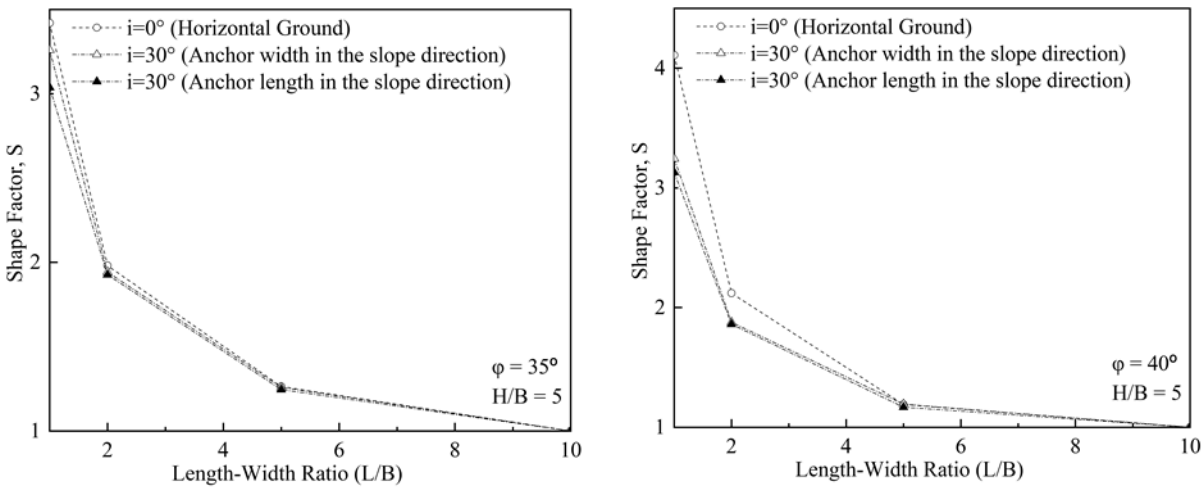


Figure 5: (1) Failure displacement in anchor width direction (a) horizontal ground, (c) *i*=30 (anchor width in slope direction), (e) *i*=30 (anchor length in slope direction); (2) Failure displacement in anchor length direction (b) horizontal ground, (d) *i*=30 (anchor width in slope direction), (f) *i*=30 (anchor length in slope direction)

For a comprehensive understanding of the effects of shape on the anchor pullout capacity, conventionally a dimensionless shape factor is used. The suitable shape factor could be used to calculate the pullout capacity/break-out factor of any other shape of anchor from the estimated capacity of strip anchor .Therefore, in this study the shape factors are computed using equation (2) ..Figures 6 (a) and (b) show the shape factors at various length-width ratios. The shape factor of the anchor decrease with the increase of length-width ratio value up to 5; thereafter it tends to be constant,



(a) (b)

Figure 6: Shape factors of plate anchors embedded in horizontal and sloping ground for (a) φ=35° and (b) φ=40°

as evident in Figures 6 (a) and (b). The obatined result agrees with the findings of Murray & Geddes (1987) and Ramaswamy (2008). A difference in shape factor can be observed between anchors embedded in horizontal ground and anchors embedded in sloping ground. For φ=40°, shape factor for square anchor embedded in horizontal ground is 4.17 which decreases to 3.28 when embedded in sloping ground. Similar trends are found for other aspect ratio of anchor.However, the shape factor is slightly affected by anchor orientation, especially at low L/B ratios (see Figures 6(a) and (b)).

7. CONCLUSION

A three-dimensional (3D) finite element analysis is carried out to investigate the effects of aspect ratio on the pullout capacity of a horizontal plate anchor embedded in the sloping ground. From this paper, the following conclusions can be drawn:

I. As the length-to-width ratio of anchors increases, their breakout factor decreases irrespective of soil conditions, sloping angle, and anchor orientation.
II. The breakout factors of the horizontal plate anchors placed in sloping ground are comparatively lower than the horizontal ground at all length-width ratios.
III. The shape factor decreases with the increase of length-width ratio upto L/B=5, and beyond that it tends to be stable. Again, the shape factor drops as the anchor is embedded in sloping ground. However, anchor orientation has a very little impact on the shape factor, especially at lower aspect ratio.

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