Study on Breakout Factors of Single Belled Anchor in Sand: Model Tests and Numerical Modelling

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Abstract. The piles are used to resist any pullout forces as well as overturning moments imposed on foundation, are idealized as anchor piles. Anchors are recommended when foundations have to bear considerable compressible loads and to carry tension anchorage in both on-land and off-shore structures. Belled anchors offer passive form of resistance against pull-out forces. In this study, experimental investigations are conducted in two different series, for determining pull-out capacity of single belled anchor models, having different anchor characteristics and embedment depths. For this study two different types of sands are used, possessing placement densities of 15.60 and 16.90 kN/m^3. The non-dimensional pull-out capacities, i.e., breakout factors in both types of sand deposits are increased with higher embedment ratios, lesser diameter ratios and lesser bell angles; but all the breakout factors are more for higher placement density than lower density for the same model. Few numerical simulations performed by Plaxis 3D modelling are found to have a satisfactory agreement with experimental breakout factors vs. model displacement relationships. The reason of variation in uplift behaviour is explored by analysis of colour shading of displacement contour from the Plaxis 3D analysis.

Keywords: Belled anchor, Breakout factor, Plaxis 3D modelling.

1 Introduction

Belled anchor pile, having an enlarged base possesses considerable load bearing capacity as well as tension anchorage. On radar tower, television tower, power pole and outdoor sign pools etc. applied imbalance wind loads may be often more than self-weight of those structures. In belled anchor pile uplift is affected by embedment ratio, diameter ratio, bell angle and density of strata. Behavior of belled anchor pile was studied in centrifugal testing chamber and under unit gravity in laboratory by Dickin and Leung (1990a, 1992b), Pal (1992), Ghosh and Bera (2010), Chae et al. (2012), Bera (2014), Bera and Banerjee (2013), and Nazir et al. (2014).

Studies were carried on the basis of experimental investigations by Balla (1961), Meyerhof and Adams (1968), Clemence and Veesaert (1977), Murray and Geddes (1987), Dickin (1988), Krishnaswamy and Parashar (1994), Sujathatha and Balamuguran (2014), and Vanitha et al. (2007) to estimate uplift capacity of plate anchors in dense sand. Based on limit equilibrium and elastic theory, mathematical models had been studied by Balla (1961), Rowe and Davis (1982), Matsuo (1967), Saran et al. (1986), Chottapadhyay and Pise (1986), Saeedy (1987), Rao and Kumar (1994), and Ghaly and Hanna (1994); it was well established that failure mechanism was controlled by combination of dead weight of failure wedge surrounding anchor offering passive form of resistance and frictional shear resistance along slip surface opposite to direction of wedge movement.

Numerical studies on uplift resistance of plate anchor were documented by Murray and Geddes (1987), Rowe and Davis (1982), Dickin and Laman (2007), and Merifield et al. (1999). Although the belled anchor piles are very popular among the geotechnical engineers, but studies to understand its behavior concisely are very limited. Till date, there is dearth of studies on numerical modelling by finite element method representing the variation in the extension of breakout sand wedge around the anchors based on characteristics of sand media.

2 Objective of the Study

In the present study an attempt is made to explore the influence of breakout factor of belled anchor pile with respect to the different density of foundation media at varying embedment ratios, diameter ratios and bell angles. Few numerical simulations performed by Plaxis 3D FOUNDATION models are analysed to justify the experimental uplift capacity vs. model displacement relationships. The reason for variation in pull-out resistance is explored by analysis of colour shading of displacement contour from the Plaxis 3D analysis based on embedment ratios, diameter ratios and bell angles.

3 Materials, Models, Testing Tank and Sand Bed Preparation

Two different types of sands are used in present study and designated as S_I and S_{II}. The dry sands are used in the present study because it is easy to conduct the tests and to maintain density of sand within the testing tank. Fig. 1 shows grain size distribution curves of S_I and S_{II} samples. From the plot of grain size distribution curves, it is noticed that S_I contains uniformly graded particles, whereas S_{II} possesses well graded particles. The experiments have been conducted as per ASTM standards to determine physical and engineering properties of these sands and results are presented in Table 1.

Belled anchor pile is identified by its geometry like, bell diameter, shaft diameter, height of bell and bell angle. The shaft of anchor is fabricated from solid shaft of mild steel having diameter (D_s) 26 mm. The bell part is manufactured from solid shaft of different diameters (D_b) 56, 68, 80 and 92 mm as required, and the shaft and belled part is joined by welding internally. The diameter ratios (D_s/D_b) of the models are 0.28, 0.38, 0.33 and 0.46. The models are having bell angles (β) of 45, 54 63 and 72°. Each of the model is installed at embedment ratio (L/D_b) of 3, 4 and 5. At the top of all the solid anchors a hollow cylindrical arrangement which is threaded internally is attached by welding to hold proving ring gently. A couple of horizontal steel strips at

180° apart from each other are welded with that arrangement and these are provided to hold dial gauges on them.

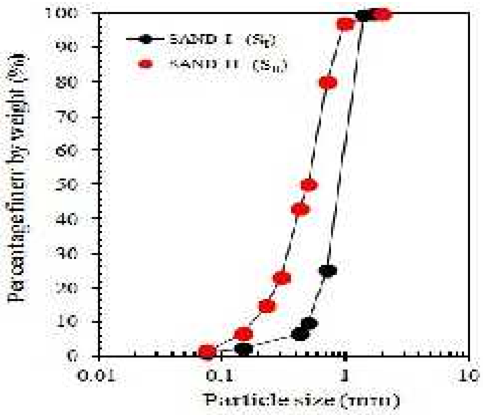


Fig. 1. Grain size distribution of S_I and S_{II} samples

Table 1. Properties of Sand I (S_I) and Sand II (S_{II})

Properties	Sand I	Sand I
Medium sand, 2 to 0.425 mm, (%)	93.50	77.00
Fine sand, 0.425 to 0.075 mm, (%)	6.50	23.00
Silt and clay, 0.075 to 0.002 mm, (%)	1.05	1.50
Effective grain size, D_{10}, (mm)	0.70	0.23
Average grain size, D_{50}, (mm)	0.93	0.65
Coefficient of curvature, C_c	0.91	1.33
Coefficient of uniformity, C_u	1.00	3.26
Name of soil (USCS)	SP	SW
Specific gravity, G_s	2.67	2.69
Minimum void ratio, $e_{min.}$	0.63	0.49
Maximum void ratio, $e_{max.}$	0.88	0.79
Void ratio, at placement density, $e_{exptl.}$	0.71	0.58
Minimum dry density, $\gamma_{min.}$ (kN/m^3)	14.20	15.00
Maximum dry density, $\gamma_{max.}$(kN/m^3)	16.50	18.20
Placement dry density, $\gamma_{exptl.}$ (kN/m^3)	15.60	16.90
Relative density D_r, (%)	64.38	63.94
Soil internal friction angle, ϕ (°)	33.00	39.50

In this study, the S_I and S_{II} are used at placement density of 15.60 and 16.90 kN/m^3 respectively, and these are achieved by raining technique (Dickin and Leung 1990, and Bouazza and Finlay 1990). Here, height of free fall from a manually operated soil tray is fixed by calibration and finalized as 700 mm in both the densities. The uniformity of sand density within model tank is checked by four wooden cubes of 80 cc in the corners of tank in different levels. The variation in density observed is ±1% only among the cubes.

3.1 Experimental program

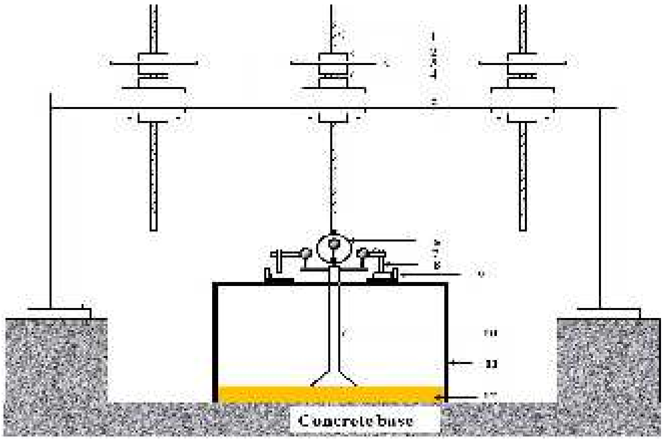
The anchors are classified as shallow and deep on the basis of depth of embedment according to Krishnaswamy and Parashar (1994), Saran et al. (1986), and Vesic (1969). In shallow anchor, failure surface reaches up to ground surface at collapsed stage, whereas in case of deep anchor, the effect of ground surface disappears. The failure pattern around shallow anchor shows general shear failure as were described by Krishnaswamy and Parashar (1994) and Vesic (1969). To carry out the study, two different series of experiments are performed to investigate the breakout factor (N_u) vs. relative displacement (D_f/D_b) behavior and net ultimate uplift capacity of model anchors buried in S_I and S_{II} deposits, each model at embedment ratio of (L/D_b) = 3, 4 and 5, each at diameter ratio (D_s/D_b) = 0.46, 0.38, 0.33, and 0.28, and possessing bell angle (β) = 45, 54, 63 and 72°. In total, 96 (= 4×4×3×2) tests are performed. For sand having medium relative density, upto embedment depth of 5 (L/D_b), the anchors behave as a shallow anchor (Chattopadhyay and Pise 1986, Saeedy 1987, Krishnaswamy and Parashar 1994, Sujathatha and Balamuguran 2014). The diameter ratio (D_s/D_b) almost 0.3 and bell angle (β) upto 72° (Dickin and Leung 1990 and 1992) was used in previous studies.

3.2 Experimental set-up, test procedure and observations

The tests conducted as mentioned earlier are meant for assessment of uplift capacity vs. model displacement behavior of models in S_I and S_{II} deposit. Fig. 2 shows the schematic diagram of experimental set-up consisting of loading frame, anchor installed inside the model tank, connected proving ring, position of dial gauges and other accessories. The loading frame is fabricated from steel channels and the base is bolted with ground for stability. A horizontal reaction beam of steel channel is attached with the vertical frames. A pulling shaft, working as screw jack which is a mechanical tool working on the principle of nut and screw motion. At the bottom of pulling shaft proving ring is attached and the model is connected with the bottom of proving ring with the models. Thus the model is suspended centrally, freely and placed vertically on sand bed within tank with the help of pulling shaft. Vertical movement of shaft is controlled by manually operated rotating circular wheel fixed with nut arrangement, and nut and screw is working on ball-bearing system. The nut along with ball-bearing arrangement is resting over the reaction beam. Due to the clock-wise motion of wheel, the model anchors move upward. Initially prior to each test, a compacted sand bed of 100 mm thick is prepared inside model tank over which the model is placed. Each model is placed horizontally on leveled sand bed. The sand is filled up to attain desired embedment depth from the surface of sand bed. The values of embedment depth for all the models are listed in Table 2. Tension proving ring of 1.0 kN capacity and a couple of dial gauges of 0.01 mm accuracy are used for measuring tensile loads and corresponding vertical displacements respectively. The dial gauges are properly fixed with magnetic bases and the magnetic bases are placed on the couple of steel bar running over the top of model tank.

3.3 Model designations

Each model is represented by a common coding system having five parts. In the first part 'M' represents model; second, third and fourth part imply the bell angle, diameter ratio and embedment ratio respectively and last part signifies the sand type (either S_I or S_{II}). For example, a 45° model placed in S_I, possessing $D_s/D_b = 0.38$ at $L/D_b = 5$ is designated as M:45-0.38-5-(S_I). The symbol M:63-0.38-3-(S_{II}) represents a 63° model is having, $D_s/D_b = 0.38$ and it is installed in S_{II} deposit at $L/D_b = 3$.



1. Long screw	2. Nut	3. Rotating wheel	4. Ball-bearing arrangement
5. Reaction frame	6. Proving ring	7. Dial gauges	8. Magnetic base
9. Magnetic base fixtures	10. Model anchor	11. Model tank	12. Sand bed

Fig. 2. Schematic diagram of the experimental set-up

4 Breakout Factors

The gross uplift capacity is the combination of self-weight of belled anchor and net uplift capacity. Self-weight of bell anchor may be different on the basis of material used to fabricate it. So, net uplift capacity is always reported as self-weight subtracted from the gross uplift capacity. The embedment ratio, diameter ratio, and bulk density of foundation media are primary parameters in the uplift resistance problem. So, these parameters are used to non-dimensionalised the uplift resistance data.

Chattopadhyay and Pise (1986) stated that N_u (breakout factor) is the function of diameter ratio and soil friction angle (ϕ) in case of plate anchor. In this study, for S_I and S_{II} deposit, net ultimate uplift capacity ($Q_u(S_I)$ and $Q_u(S_{II})$) are presented as breakout factor ($N_{u.obs.}(S_I)$ and $N_{u.obs.}(S_{II})$), non-dimensionalised by density (γ_I and γ_{II}), embedment depth (L), belled base area (A_b), and hence expressed in the following form:

$$N_{u.obs.}(S_I) = \frac{Q_u(S_I)}{A_b \gamma_I L} \qquad \text{... [8.1]}$$

$$N_{u.obs.}(S_{II}) = \frac{Q_u(S_{II})}{A_b \gamma_{II} L} \qquad \text{... [8.2]}$$

The similar expression is used by Dickin and Leung (1990, 1992), Pal (1992) and Bera and Banerjee (2013).

5 Numerical Analysis by PLAXIS 3D FOUNDATION

A wide range of problems in continuum mechanics can be analysed by the finite element method. Dependent on element size, shapes, distribution of cluster and mesh refinement the sensitivity and accuracy of numerical models can be controlled. The method of programming is completely based on iterations and matrix through mathematical operations.

The FEM based professional software called PLAXIS 3D FOUNDATION is used for the models to represent the failure mechanism and breakout factor vs. relative displacement behavior of anchors. Soils have a tendency to behave highly non-linear way under load and so, their behaviour can be modelled at several levels of sophistication. In this study, Mohr-Coulomb model is used to represent the soil behaviour. The soil model involves five basic parameters namely, Young's modulus (E), Poissons ratio (ν), cohesion (c), friction angle (ϕ) and dilatancy angle (ψ). The density of sand deposits play a vital role, since the upward movement of anchor is primarily resisted by the dead-weight of material resting over it. The values of Young's modulus and Poisson's ratio of soil affect the deformation characteristics under applied tension, which in turn may affect the mode of ultimate failure. The mild steel used to fabricate the anchors is modelled by linear elastic material. The present study is concentrated on the uplift resistance due to anchor movement, not due to adhesion with anchor shaft; so, soil-shaft adhesion is neglected. The size factor of the anchors is 1/10. In this present study, the failure mechanism is an immediate breakaway case. At the completely collapsed stage, the formation of surface heaves is presented in Fig. 3 for models M:45-0.33-4-(S_I).

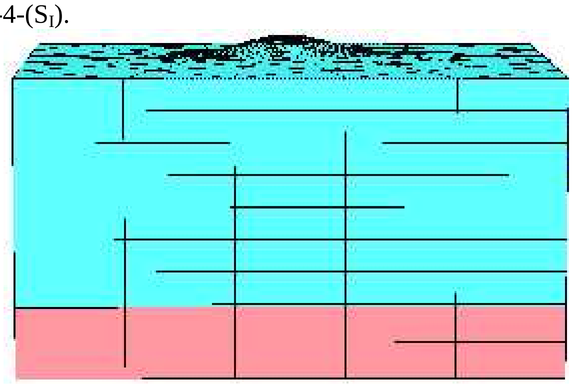


Fig. 3 Displacement field for model M:45-0.33-4-(S_I)

From the Figs. 4 and 5, it is noticed that each colour shading represent the displacement efficiency of the surrouding sand and the extension of same colour shading is higher in S_{II} deposit than in S_I deposit. This phenomenon reflect that the formation of failure wedge is higher in S_{II} deposit than in S_I deposit. This phenomenon is identical as reported by Dickin and Leung (1992) and Nazir et al. (2015). Hence, it may be stated that the plaxis results are correct and may be used for parametric study.

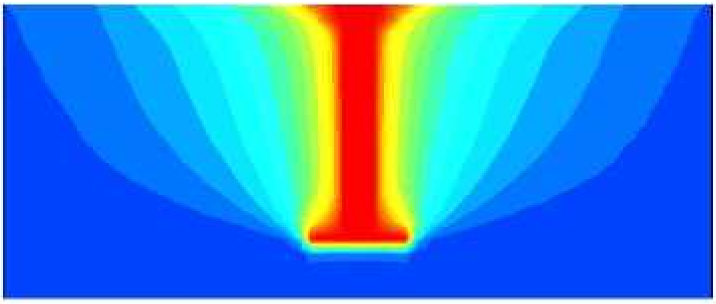


Fig. 4. Colour shading of total displacement contours for model M:45-0.33-5-(S_I)

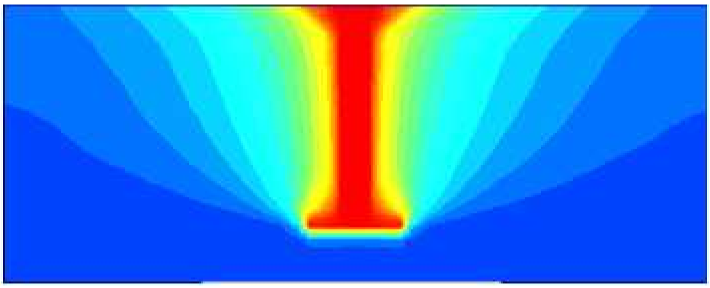


Fig. 5. Colour shading of total displacement contour for model M:45-0.33-5-(S_{II})

6 Results and Discussions

6.1 Observations on breakout factor vs. relative displacement behaviour

The typical breakout factor vs. relative displacement behaviour for S_I and S_{II} deposits are presented in Figs. 6 and 7 for models M:54-0.46 and M:63-0.28 respectively both at L/D_b of 3, 4 and 5. In general, the curves pass through three stages. Initially, in the curves, linear part is presenting true elastic response where vertical deformation of anchor is very less and thereafter linear part trying to be approximately curvilinear shape showing comparatively higher rate of deformation, and finally, the elasto-plastic response is seen with truly curvilinear shape at collapsed stage with rapid growth of plastic region as well as highest rate of deformation up to that phase. The natures of curves are similar as explained by Rowe and Davis (1982) in sand for plate anchors. At collapse stage, strength mobilization is lower than the rate of increment of displacement. It was explained by Nazir et al. (2014) that at the collapse stage, there is an immediate formation of cavity underneath the anchor base under applied vertical tension in sand deposit. Hence, at plastic stage immediate breakout of sand wedges has been occurred. From the figures, it is also revealed that behavior of breakout factor vs. relative displacement response is independent of L/D_b, D_s/D_b, β and density of sand deposits.

6.2 Breakout factor (N_u) of belled anchor piles influenced by embedment ratio (L/D_b) depending on density of sand deposit

The plots of breakout factor vs. embedment ratio for S_I and S_{II} are illustrated in Fig. 8 for models M:45-0.33, at L/D_b of 3, 4 and 5. It reveals that with the increase in the value of L/D_b, for same anchor properties the breakout factor of belled anchor pile gradually shifted upward irrespective of D_s/D_b, β and sand density. For M:45-0.33,

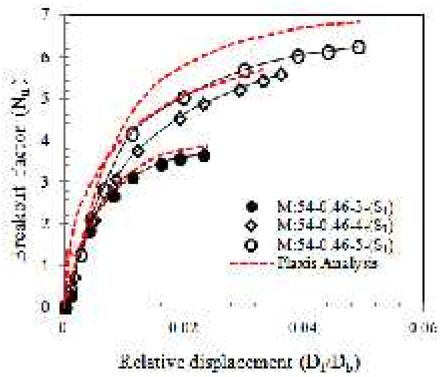


Fig. 6. Breakout factor vs. relative displacement relationship for model M:54-0.46 buried in S_I and S_{II} deposits at L/D_b = 3, 4 and 5

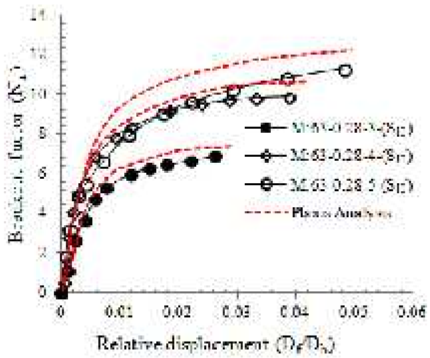


Fig. 7. Breakout factor vs. relative displacement relationship for model M:63-0.28 buried in S_I and S_{II} deposits at L/D_b = 3, 4 and 5

the primary increment (for L/D_b changed from 3 to 4) is 91.61% and secondary increment (for L/D_b changed from 4 to 5) is 41.24% in S_I deposit; for the same model, the primary increment is 100.34% and secondary increment is 57.43% in S_{II} deposit. A similar trend is also found from Plaxis analysis. The similar pattern was noticed by Ilamparuthi and Dickin (2001), Mittal and Mukherjee (2013), Dickin and Leung (1990),Vanitha et al. (2007), Pal (1992), and Ghosh and Bera (2010), Bera (2014), Nazir et al. (2014) and Ilamparuthi and Dickin (2001) in cohesionless foundation soil for helical screw anchor and belled anchors in sand. The similar pattern in the values of uplift capacity was studied by Murray and Geddes (1987), Dickin (1988), Sujathatha and Balamuguran (2014), Niroumand et al. (2014) and Mittal and Mukherjee (2013) for plate anchors in dry sand deposit. But in this figure, for M:45-0.33 at L/D_b = 3, 4 and 5, the value of N_u (S_{II}) is higher than N_u (S_I) 77.35, 73.65 and 70.75% respectively. The reason behind the increasing trend of breakout factors has already been explained in article § 5. Numerical Analysis by PLAXIS 3D FOUNDATION.

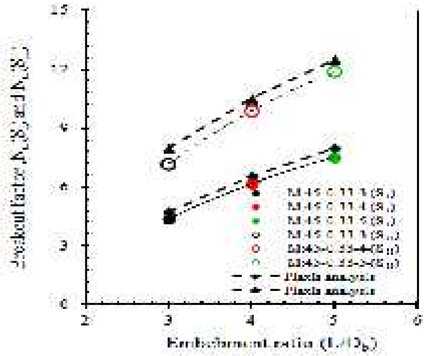


Fig. 8. Breakout factor vs. embedment ratio for model M: 45-0.33 buried in S_I and S_{II} at L/D_b = 3, 4 and 5

6.3 Breakout factor (N_u) of belled anchor piles influenced by diameter ratio (D_s/D_b) depending on density of sand deposit

The plots of breakout factor (N_u) vs. diameter ratio for S_I and S_{II} are presented in Fig. 9 for 54° belled anchor piles at L/D_b of 5, all of these models are having D_s/D_b of 0.28, 0.33, 0.38 and 0.46. A similar trend is also found from Plaxis analysis. In this figure, for the models of 54° belled anchor piles at L/D_b of 5, due to decrease in the value of D_s/D_b from 0.46 to 0.33, 0.33 to 0.38 and 0.38 to 0.46, breakout factor is changed from 6.26 to 6.73, 6.73 to 7.15, 715 to 7.08 respectively, in S_I deposit. For similar decrease in the values of D_s/D_b in S_{II} deposit, breakout factor is changed from 10.59 to 11.89, 11.89 to 11.43, 11.43 to 11.81 respectively. The similar trend in the values of breakout factor based on experimental data was reported by Dickin and Leung (1990), Pal (1992), Nazir et al. (2014), and Ilamparuthi and Dickin (2001) for belled anchors installed in dry sand. But in this figure, for M: 54-0.28, M: 54-0.33, M: 54-0.38 and M: 54-0.46 at L/D_b = 5, the value of N_u (S_{II}) is higher than 80.73, 73.22, 91.33 and 83.25% respectively. The reason behind the increasing trend of breakout factors has already been explained in article § 4. Numerical Analysis by PLAXIS 3D FOUNDATION.

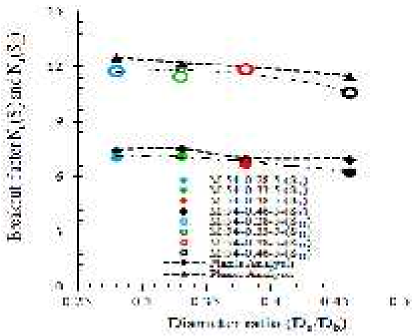


Fig. 9. Breakout factor vs. diameter ratio for model M: 54-0.28 buried in S_I and S_{II} at L/D_b = 3, 4 and 5

6.4 Breakout factor (N_u) of belled anchor piles influenced by bell angle (β) depending on density of sand deposit

The graphical plots in Fig. 10 show that for belled anchor piles breakout factors gradually decrease for higher bell angles, in the models of D_s/D_b = 0.38 at L/D_b = 5, and installed in S_I and S_{II} deposits. A similar trend is also found from Plaxis analysis. The breakout factors of models are reduced approximately 7.00 to 10.00% in both types of sand when the bell angle is increased from 45 to 63°. Dickin and Leung (1992), and Nazir et al. (2014) noticed negligible reduction in uplift capacity of belled anchor pile due to change in bell angle from 45 to 60° and 22 to 63° respectively. But in case of present study, when belled angle increased from 63 to 72°, in most of the cases uplift capacities decreased within the range of approximately 17.00 to 22.00% and 15.00 to 20.00% in S_I and S_{II} deposits respectively. Dickin and Leung (1992) also reported that there was a rapid decrease in uplift capacity beyond bell angle of 62°. The uplift capacities of the anchors are higher for 45, 54 and 63° anchors than 72° anchors, being independent of L/D_b and D_s/D_b in both S_I and S_{II} deposits of the present study. But in this present study, for higher density of S_{II}, the value of N_u (S_{II}) is higher than N_u (S_I) (i.e., in lesser dense sand, S_I) as explained in article § 5. Numerical Analysis by PLAXIS 3D FOUNDATION.

In this figure for the models M:45-0.38-5, M:54-0.38-5, M:63-0.38-5 and M: 72-0.38-5, N_u (S_{II}) is higher than N_u (S_I) 91.00, 92.5, 91.65 and 93.34% respectively.

7 Concluding Remark

The following significant conclusions may be drawn as listed below:

- The PLAXIS 3D FOUNDATION reflct that the formation of failure wedge is higher in S_{II} deposit than in S_I deposit.

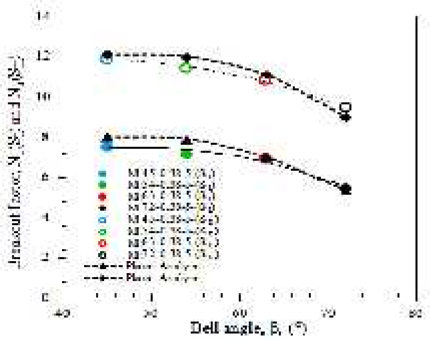


Fig. 10. Breakout factor vs. bell angle for 45, 54, 63 and 72° model buried in S_I and S_{II} deposit at L/D_b = 3, 4 and 5

- The breakout factor vs. relative displacement relation is similar in pattern from PLAXIS 3D FOUNDATION analysis and experimetal observations regardless the density of sand, embedment ratio, diameter ratio and bell angle; same failure mechanism is responsible for uplift resistance in sand irrespective of the parameters considered in this study. Due to higher density of buried sand, breakout factor is increased at lesser relative failure displacement irrespective of embedment ratio, diameter ratio and bell angle. For higher embedment ratio, higher breakout factor is obtained irrespective of diameter ratio and bell angle in both density of sand of present study. With increase in diameter ratio, a gradual decreasing trend in breakout factor is found regardless embedment ratio and bell angle in both the sands at their placement density. With a gradual steeper bell angle (from 45 to 63°), for specific diameter ratio and embedment ratio, breakout factor become gradually lesser regardless the density of foundation media. When belled angle increased from 63 to 72°, uplift capacities decreased significantly in both the sands at their placement density. All the silent features of this experimental study is in good agreement with PLAXIS 3D FOUNDATION analysis.

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