An Experimental Study on Uplift Capacity of Axisymmetric Plate Anchors in Well Graded Sand at Different Relative Density and Embedment Ratio

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Abstract

Earth anchors of different types are used in various geotechnical applications to provide uplift resistance and structural stability against axial and lateral forces. Earth anchors are primarily designed to resist pull-out force. The pull-out resistance depends upon various factors such as anchor type, the shape of an anchor, direction of application of pull-out force, density of soil, etc. Various theoretical development occurred in the past few decades where the above factors are considered in a different quantitative manner. The present study aims to compare the theoretical development of different theories for horizontal plate anchors and the influence of the factors contributing to uplift resistance by both analytical and theoretical methods. The comparative summary is provided for respective analytical methods and factors considered to calculate uplift resistance. Scaled model test performed on circular axisymmetric horizontal plate anchor in cohesionless soil. Uplift load versus embedment ratio was analyzed for different theoretical methods. The analytical results were compared to both experimental and Plaxis 2D software results. The Plaxis 2D gives the most conservative results and Down and Cheiurzzi propose the highest uplift load for the same embedment ratio. Finally, the relationship between the angle of internal friction (ϕ) to uplift cone angle (θ) is proposed for the type of soil used in this study for two different plate sizes. Results of the Experimental Laboratory Test show that Uplift Load (Qu) increases with increased Embedment Depth and Relative Density. Analytical theories like Meyerhof& Adams, Downs & Chieurzzi, Saeedy's & Balla's gave nearer higher values whereas Veesaert & Clemence's gave nearer low Uplift Load (Qu)compared with Experimental ones. For F.E.M-based software Plaxis (2D) gave lower Uplift Load (Qu) than Experimental ones.

Introduction

Pullout resistance of horizontal plate anchors was first investigated by Balla (1961). Turner (1962), Bakar and Kondar (1966), Matsuo ((1967) conducted scale model experiments to understand dimensional analysis to derive ultimate uplift load (Qu) for circular plate anchors. The large number of experimental investigations were carried out by Bemben & Kupferman (1975), Das and Seeley (1975), Das (1978), Rowe and Davis (1982), Clemence (1983), Datta and Sing (1984) Das et.al. (1985), Chattopadhyay and Pise (1986), Barua & Chattopadhyay (1989), Ghaly et al (1991), Ghaly & Hanna (1994), Rao & Kumar (1994), Sharma & Pise (1994) Handojo & Chang (1997), Shankar et al (2007), Kumar and Kouzer (2008).

Many analytical and experimental studies have been accomplished in this area notably by Mors, H. (1959), Mayerholf & Adams (1968), Vesic (1971), Clemence & Veesaert (1977), Saeedy (1987), Das (2007), Deshmukh & Chaudhary (2010), Das & Shukla (2013).

The installation of anchor plates depends on the direction of load applied. Anchor plates may be horizontal to resist vertically-directed uplifting load, inclined to resist axial pullout load, or vertical to resist horizontally-directed pullout load. The process of installing an anchor plate is tedious and not an easy task compared to helical but still has wide applications in geotechnical engineering. During the installation process, the soil should be excavated to the required depth and then backfilled with good soil after placing the anchor plate.

Anchors can be installed by excavating the ground or by drilling/driving to the required depth and then backfilling and compacting with good quality soil this type is referred to as backfilled plate anchors. In many cases, plate anchors may be installed in excavated trenches. These anchors are then attached to tie rods which may either be driven or placed through augured holes, anchors placed in this way are referred to as direct bearing plate anchors.

Anchor plates are categorized based on two aspect:

I. According to shape

II. According to application.

1. According to shape

Soil anchors are installed in different shape like circular (axisymmetric plates), square & rectangular. The shape is determined based on bearing capacity of anchor plates and the inflicted tension against the soil in which it is located. These anchors are then attached to tie rods which may either be driven or placed through augured holes in to the ground.

2. According to Application

Anchor plate may be horizontal to resist vertically-directed uplifting load, inclined to resist axial pullout load, or vertical to resist horizontally-directed pullout load, as shown in Figure

A. Balla's Theory

Based on some early theories with subsequent variations, Balla (1961) suggested for shallow circular anchors, that the failure surface in soil will be as shown in Fig. 2.4. Where aa' and bb' are the arc of the slip surface. The radius (r) of this arc is equal to,

$$r = \frac{H}{\sin(45 + \frac{\Phi}{2})}$$

The angle α is equal to (45 − Φ/2).

Balla proposed the net ultimate uplift capacity of the anchor is the sum of two components: (a) weight of the soil in the failure zone and (b) the shearing resistance developed along the failure surface.

$$Q_u = \gamma H^3 \left[F_1\left(\Phi, \frac{H}{D}\right) + F_3\left(\Phi, \frac{H}{D}\right) \right],$$

Where, the sum of the function F_1 and F_3 are obtained by figure given below

The breakout factor N_q is defined as,

$N_q = \frac{Q_u}{\gamma AH}$

Where,

A = Area of the plate anchor.

The breakout factor increases with H/D ratio up to N_q^* at $H/D_{(cr)}$. Based on Balla's method, the shallow anchor plates are defined at $H/D \leq H/D_{(cr)}$ and deep anchor plates at $H/D \geq H/D_{(cr)}$.

B. Saeedy's Theory

An ultimate holding capacity theory for circular plate anchors embedded in sand was proposed by Saaedy (1987) in which the trace of the failure surface was assumed to be an arc of a logarithmic spiral.

According to Saeedy (1987), during the anchor pull out the soil located above the anchor gradually becomes compacted, in turn increasing the shear strength of the soil and, hence, the net ultimate uplift capacity. For that reason, he introduced an empirical compaction factor which is given in the form.

$$\mu = 1.044 D_r + 0.44$$

Where,

D_r = relative density of compaction

μ = compaction factor

Thus, the actual net ultimate capacity can be expressed as

$$Q_{u(actual)} = \left(F_q \gamma AH\right) \mu$$

C. Meyerhof and Adam's Theory

Meyerhof and Adams (1968) proposed a semi theoretical relationship for estimation of the ultimate uplift capacity of strip, rectangular and circular anchors. It needs to be pointed out that this is the only theory presently available for estimation of Q for rectangular or square anchors. The principles of this theory can be explained by considering a shallow strip anchor embedded in sand as shown in Fig.

The angle α depends on several factors such as the relative density of compaction and the angle of friction of the soil, and it varies between (90° - Φ/3) to (90° − 2Φ/3).

Here, following forces are the reason for ultimate uplift capacity,

a) The weight of the soil, W = ⍰ * 1 * B * H (for unit length), and

b) The passive force P_p' per unit length along the faces ab and cd. The force P_p' is inclined at an angle α to the horizontal. For an average value of α = 90 - Φ/2, the magnitude of δ is about (2/3) Φ.

- For strip anchors, the area A per unit length is equal to 1 x B = B. So (from Das and Seeley, 1975),

$Q_u = W + K_u \gamma H^2 \tan \Phi$

Where,

Ku = Nominal uplift coefficient ($K_u \tan \Phi = K_{ph} \tan \delta$)

K_{ph} = Horizontal component of the passive earth pressure (P_p')
The variation of the nominal uplift coefficient K_u with the soil friction angle Φ is shown in Fig. 8

- For circular anchors, Equation for strip anchors can be modified as,

$Q_u = W + \frac{\pi}{2} S_F \gamma D H^2 K_u \tan \Phi$

Where,

$S_F = 1 + m\frac{H}{D}$

m = Coefficient which is a function of the soil friction angle Φ shown in Fig.
The breakout factor N_q can be derived from following Equation,

$N_q = \frac{Q_u}{\gamma A H}$

So, $Nq = 1 + 2\left[1 + m\left(\frac{H}{D}\right)\right]\left(\frac{H}{D}\right)K_u \tan \Phi$

- For rectangular anchors having dimensions of L * B (length * width), the net ultimate capacity and breakout factor can be expressed as,

$Q_u = W + \gamma H^2 \left(2 S_F B + L - B\right) K_u \tan \Phi$

$N_q = 1 + \left\{\left[1 + 2m\left(\frac{H}{B}\right)\right]\left(\frac{B}{L}\right) + 1\right\}\left(\frac{H}{B}\right) K_u \tan \Phi$

Experimental observations of Meyerhof and Adams on circular anchors showed that the magnitude of S_F * Ku = [1 + m (H/h)] * K_u for a given friction angle Φ increases with H/B to a maximum value at H/B = $(H/B)_{cr}$ and remains constant thereafter. This means that, beyond $(H/B)_{cr}$, the anchor behaves as a deep anchor. These $(H/B)_{cr}$ values for square and circular anchors are given in Fig. 10

D. Veesaert and Clemence's Theory

Based on laboratory model tests results, Veesaert and Clemence (1977) suggested that for shallow circular anchors the failure surface at ultimate load may be approximated as a truncated cone with an apex angle as shown in Fig. 11. With this type of failure surface, the net ultimate uplift capacity can be given as under

$$Q_u = \pi \gamma K_0 (tan\varphi) \left(cos^2\frac{\varphi}{2}\right)[\frac{H^3 \tan\left(\frac{\varphi}{2}\right)}{3} + \frac{hH^2}{2}]$$

Where,

V = volume of the truncated cone above the anchor

K_0 = coefficient of lateral earth pressure

$$\text{V} = \frac{\pi\{\backslash\text{rm H}\}}{3}\left[h^2 + \left(h + 2Htan\frac{\varphi}{2}\right)^2 + (h)\left(h + 2Htan\frac{\varphi}{2}\right)\right]$$

$$F_q = \left\{4K_0 (tan\varphi)(cos^2\frac{\varphi}{2}\right)\left(\frac{H}{h}\right)^2\left[\frac{0.5}{\frac{H}{h}} + \frac{tan\frac{\varphi}{2}}{3}\right]\}$$

+$[4 + 8\left(\frac{H}{h}\right)tan\frac{\varphi}{2} + 5.333\left(\frac{H}{h}\right)^2 tan^2\frac{\varphi}{2}]$ –Eq. (1)

$F_q = \frac{Q_u}{\gamma AH}$ –Eq. (2)

Veesaert and Clemence (1977) suggested that the magnitude of K may vary as 0.6 to 1.5 with an average value of about 1.

Figure shows the plot of $F_q vs \frac{H}{h}$ with $K_0 = 1$. In this plot it is assumed that $(H/h)_{cr}$ is the same as that given by Meyerhof and Adams (1968).

E. Mor's Theory (Soil Cone Method)

Some research to determine uplift capacity of anchor plate Q_u has been done only on shallow circular plate anchor in earlier cases by Mors (1959), Downs & Cheiurzzi (1966) and other researchers. Mors (1959) proposed that the failure surface in soil at ultimate load may be approximated as a truncated cone having an apex angle of θ = 90° + Φ/2 shown in Fig. 2.1. Later, Downs & Cheiurzzi suggested that the apex angle θ may be equal to 60° shown in Fig. 2.2.

The net ultimate uplift capacity can be considered equal to the weight of the soil located inside the failure surface. So,

Q_u = ▯ * V

Where,

▯ = Unit weight of soil

V = Volume of soil in truncated cone,

h = Diameter of anchor plate
For Downs & Chieurzzi theory,

$$V = \frac{\pi}{3} H^3 \left\{ h^2 + [h + 2H \cot 60]^2 + h(h + 2H \cot 60) \right\}$$

Methodology

Well graded sand used to perform experimental study on uplift anchors embedded in sand as it was observed in most of the experimental studies was performed in well graded sand. Different size of partials offers natural behavior of transfer of frictional properties against the uplift phenomenon which is not possible is same size of particles size in experimental study.

Table.1. Soil Properties.

Soil to be used	Well Graded Sand (SW)
Location of sand	Sand from Sevalia, Gujarat, India
Coefficient Of Uniformity, (Cu)	8.33
Coefficient Of Curvature, (Cc)	1.21
Specific Gravity, G	2.649
Minimum Density, □$_{min}$	1.630 gm/cm^3
Maximum Density, □$_{max}$	1.897 gm/cm^3
70% Relative Density, D_r	1.808 gm/cm^3
85% Relative Density, D_r	1.851 gm/cm^3
Angle of Internal Friction, (□) for 70% Relative Density,	41.28°
Angle of Internal Friction, (□) for 85% Relative Density,	46.45°

The schematic diagram shown in Fig-15. The Fe 415 steel Channel Section was used to manufacture the loading frame and it is manufactured in such a way that it behaves monolithic at the time of application of load. The Plaxi-Glass tank is also designed to behave relatively stiff while filling the tank with sand and also at the time of application of the load. Detailed information of the component part of the set-up is depicted below.

1. Loading Frame

Loading Frame is design for more than 50kN load capacity. Chain Pulley Block with 30kN capacity is hang on frame for apply uplift load. It is made of C-channel section with angle section bracing.

2. Plaxi-glass Tank

Tank is arranged to generate ground condition by filling sand. Dimension of the tank is 1.2m * 1.2m * 1.2m. Base of the tank is made of iron steel plate and side of the tank is made of Plaxi-glass sheet with support of angle section.

3. Anchor plate with Rod

Anchor Plate and Rod is made of Mild steel material. It is designed for 30kN loading condition. Dimension of the anchor plate are 0.15m radius & 0.30m radius. Dimension of Anchor Rod is 1.2m.

4. Proving ring

Proving Ring with 50kN capacity is used to measure the load. It is connected between chain pulley block's hook and anchor rod.

5. Dial Gauge

Dial Gauge with 0.01mm least count is used to measure the anchor plate's vertical displacement.

The Anchor plate was placed at pre-fixed depth and then sand is poured into the tank from fixed height evenly maintaining the smooth movement of hopper and even thickness of layer. The density inside the tank was measured before performing the experiment by impact penetrometer to ensure that the designed density is achieved or not. If the density is not matching with designed density then the layer above anchor replaced and again filled up to achieve design density of sand.

Table:2 Number of experiments performed in laboratory.

Sr No.	Plate Size (D) m	Density Type	Relative Density (%)	Embedment Depth (m)
1	0.15	Dense	70	0.3, 0.45, 0.60
		Very Dense	85	0.3, 0.45, 0.60
2	0.3	Dense	70	0.3, 0.45, 0.60
		Very Dense	85	0.3, 0.45, 0.60

Experimentation & Graphical Representation

The uplift load was applied by mechanical motor arrangement with constant load. The test is considered to be stress controlled test where the readings of uplift load was measured with respect to displacement. To ensure reliability of the results of experiments each test was repeated three times and average results were considered for analysis.

The experimental study is classified as per the plate size and depicted its behavior for Uplift load versus displacement. (Fig- 17 and 18). The most common behavior extracts from the experimental result is the uplift capacity increase with anchor plate size as well as density of soil. There is increase in uplift capacity with increase in embedment depth of anchors. There is 1.3-time approximate increase in uplift capacity of anchors by increase in anchor plate size to double. For shallow embedment and less density, the displacement is very less compared to reverse scenario. It is obvious that anchors placed at 0.3m depth doesn't offers any uplift capacity.

The experimental studies are conducted as small-scale test within the laboratory environment. The uplift anchor at real scale and field stress scenario the stress strain behavior may exhibit in different way than the results depicted here. Experimentation on real scale anchors need to consider scale effect.

Formation of heaving is predominant for 0.15 m plate (photograph-2) and clearly visible on surface while edge boundary for failure is visible for 0.30 m plate where heaving is not large (photograph-3).

3. Modelling in PLAXIS

For circular plate anchor Axisymmetric model with 15 node elements were selected. Gravitational acceleration was selected as $9.8 m/s^2$. Grid spacing was adopted as 0.025m considering snap intervals as one. Soil stiffness E_{ref} was assumed to be $7000.00 kN/m^2$ and poisons ratio to be 0.3. The material parameters of anchor plate is given in table-3 and Interface properties of sand and plat is tabulated in table-4.

Table.3. For Axisymmetric Anchor Plates of Size (1) 0.15m, (2) 0.30m**.**

Axisymmetric Anchor Plate Input Parameters		
E	2.10E+06	kN/m^2
A	0.015	m^2/m
EA	3.15E+04	kN/m
I	2.8125E-07	m^4/m
EI	5.91E-01	$kN*m^4/(m^2*m)$
w	1.156759835	kN/m/m
v	0.3	

Table.3. Values used for Anchor Plates & Sand in Modelling, for Sand of Relative Densities (1) 70%, (2) 85%.

Soil	Sand, (70% D_r)		Sand, (85% D_r)	
Type	Undrained		Undrained	
Model	Mohr Coulomb		Mohr Coulomb	
kx	1	m/day	1	m/day
ky	1	m/day	1	m/day
E	7.00E+03	kN/m/m	9.60E+03	kN/m/m
v (nu)	0.3		0.3	
c	0	kN/m/m	0	kN/m/m
Angle of Friction	41.28	°	46.45	°
Angle of Dilatancy	11.28	°	16.45	°

PLAXIS 2D modelling software was used to ensure the stiffness of the anchor plate to simulate the field conditions. Triangular meshing elements were selected. Mohr -coulomb sand interface was selected and sand was assumed to be elastic material.

The model is assumed to be symmetrical about vertical axis and analyzed accordingly (fig-19). The bottom part of the sand -tank interface assumed to be restrained and horizontal interface assumed to be free field boundary conditions.

Output mesh shows deformed mesh above the anchor plate and heaving (fig-21) is clearly visible on top of the boundary level.

Uplift Load v/s Displacement for all Analytical Theories, F.E.M based Software Plaxis & Experimental Results

The analytical results were obtained by constructing Microsoft excel for Mayerholf and Adams, Balla, Down and Cheiurzzi, Veesaert and Clemence, and Saeedy's theory. The results of above analytical methods were compared with Plaxis 2D and experimental study and plotted below.

Discussion

The experimental, analytical and software analysis were compared in a same plot. Plaxis 2D gives most conservative results compared to rest of the analytical solutions. Downs and Cheiruzzis's results were too high compared to rest of the methods. Balla, Mayerholf, Veesaert

S and Saeedy's analytical results seem to be follow same trend of result. The analytical, experimental and software analysis for uplift capacity of model ground anchor shows almost similar behavior with respect to various densities of sand. It is evident that the Plaxis (2D) gives most conservative results for uplift capacity, while Downs and Cheiurzzi gives over safe values for uplift capacity of ground anchors.

Table.4. Proposed failure angle from peak uplift load

Φ, °	Dry unit weight, γ (kN/m3)	Embedment Depth,H (m)	Width, B	θ(°)	B1	B2	Volume (m3)	Dead Weight (kN)	θ_{avg}
34.22	16.39	0.3	0.15	27.46	0.462	0.15	0.030	0.50	26.68
		0.5		27.34	0.667		0.095	1.55	
		0.8		25.26	0.905		0.261	4.27	
42.09	17.20	0.3		30.69	0.506		0.035	0.61	31.23
		0.5		30.43	0.737		0.113	1.94	
		0.8		32.59	1.173		0.420	7.22	
45.62	18.05	0.3		31.67	0.520		0.037	0.67	34.20
		0.5		33.67	0.816		0.135	2.44	
		0.8		37.27	1.368		0.560	10.10	
34.22	16.39	0.3	0.3	38.71	0.631	0.3	0.068	1.11	34.63
		0.5		34.81	0.845		0.176	2.89	
		0.8		30.37	1.088		0.426	6.99	
42.09	17.20	0.3		42.00	0.690		0.077	1.33	37.43
		0.5		36.04	0.878		0.187	3.22	
		0.8		34.24	1.239		0.533	9.16	
45.62	18.05	0.3		42.76	0.705		0.080	1.44	40.78
		0.5		40.02	0.990		0.228	4.11	
		0.8		39.57	1.472		0.720	12.99	

Conclusion

- **Meyerhof & Adams** analytical results are **20% to 35%** higher than experimental results for dense and very dense sand conditions.
- **Balla's** analytical results are in good agreement to experimental results for both dense and very dense sand conditions.
- **Downs and Chieurzzi** analytical results are **15% to 50%** higher than experimental results for dense and very dense sand conditions.
- **Saeedy's** analytical results are **10% to 20%** higher than experimental results for dense and very dense sand conditions.
- Analytical theories during calculation took higher frictional angle (to the vertical) which give **larger passive zone** compared with actually occurred in tank during experimental model test, so analytical results are higher than experimental results.
- **Veesaert & Clemence's** analytical results are **10% to 20%** lower than experimental results for dense and very dense sand conditions.
- Experimental Pullout Test clearly indicates that the Uplift Load (Qu) increases with increase in Plate Size, Relative Density and Embedment Depth.
- Displacement corresponding to Peak Uplift Load (Qu) increases with increase in Embedment Ratio.
- The experimental results are **30% to 75%** higher than results obtained from F.E.M based software **Plaxis** for dense and very dense sand conditions.
- Plaxis software uses Mohr-Coulomb Model which is used for first approximation of soil behavior and it takes account of young's modulus (E), which remains constant with embedment depth, so there is just linear increase in results coming from Plaxis, so they are much lesser compared to experimental results.
- As per the Pullout Test results, it clearly indicates that for axisymmetric anchor plates the failure angle to the vertical increases with decrease in Size of Plate, and with increase in Relative Density & Embedment Ratio.
- Plate size 0.15 m, $\boldsymbol{\theta = 0.55\Phi + 4.43}$
- Plate size 0.30 m, $\boldsymbol{\theta = 0.55\Phi + 1.03}$

Declarations

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Conflict of Interest: The authors declares that there is no conflict of interest regarding any of the matter incorporated in this paper.

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Supplementary

Photo 1-3 are available in Supplementary Files section.

Figures

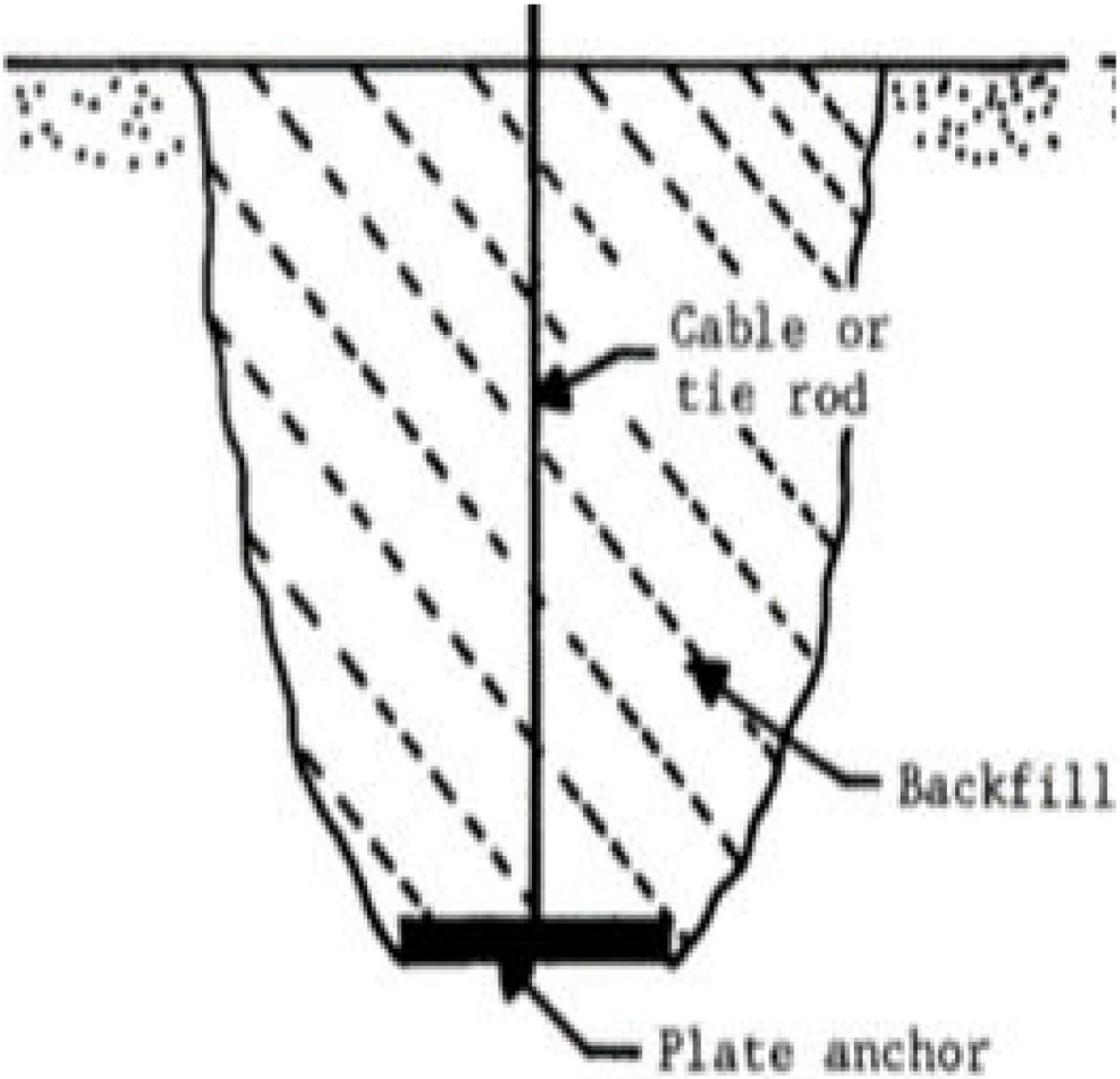

Figure 1

Installation of Plate Anchors: Backfilled Plate Anchor

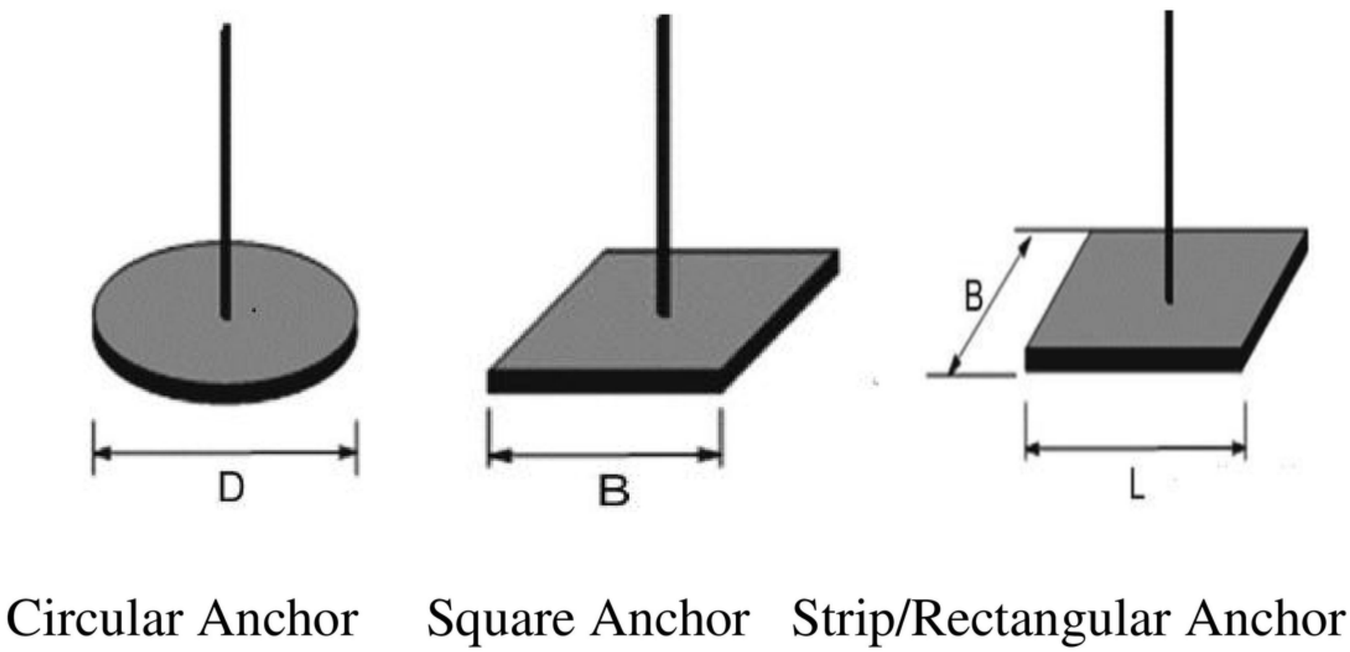

Figure 2

Types of Anchor Plate according to Shape.

Figure 3

Types of Anchor Plate according to Application.

Figure 4

Failure surface assumed by Balla for Shallow Circular Anchor Plate.

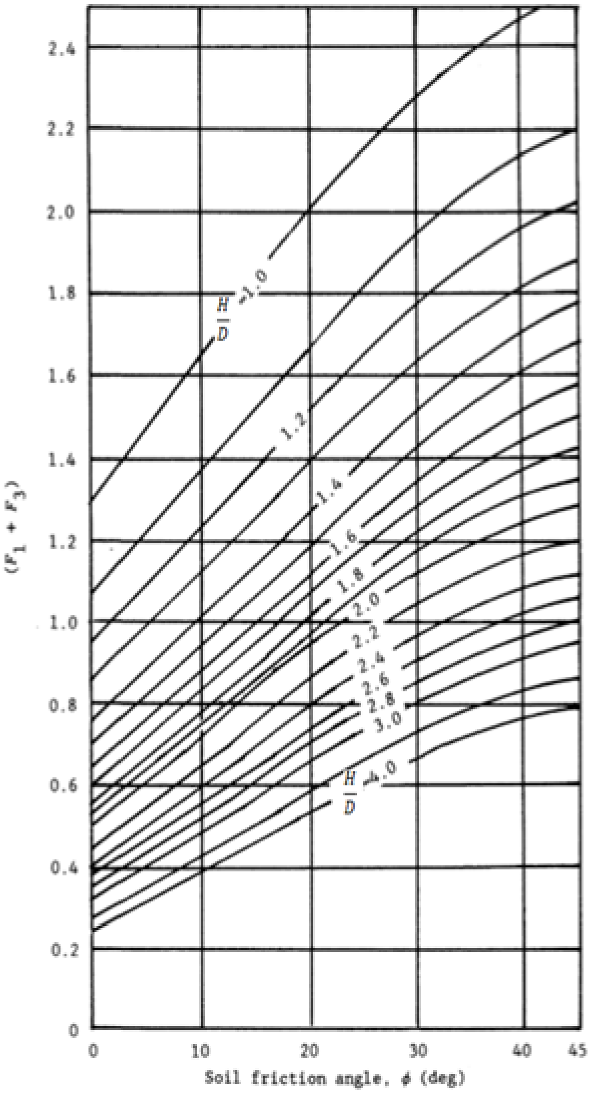

Figure 5

Variation of $F_1 + F_3$ based on Balla's theory

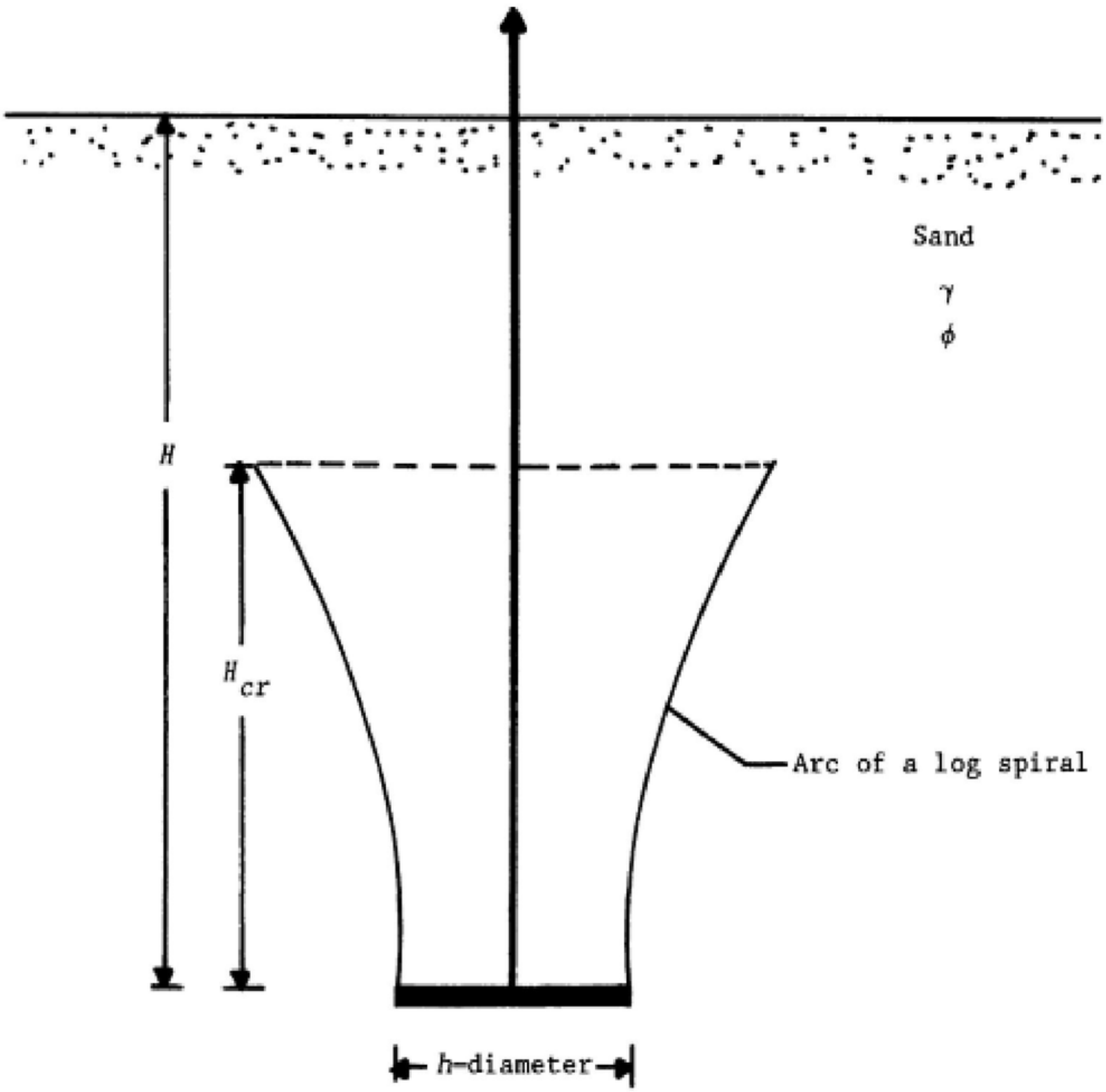

Figure 6

Saeedy's Theory for Circular Plate Anchors.

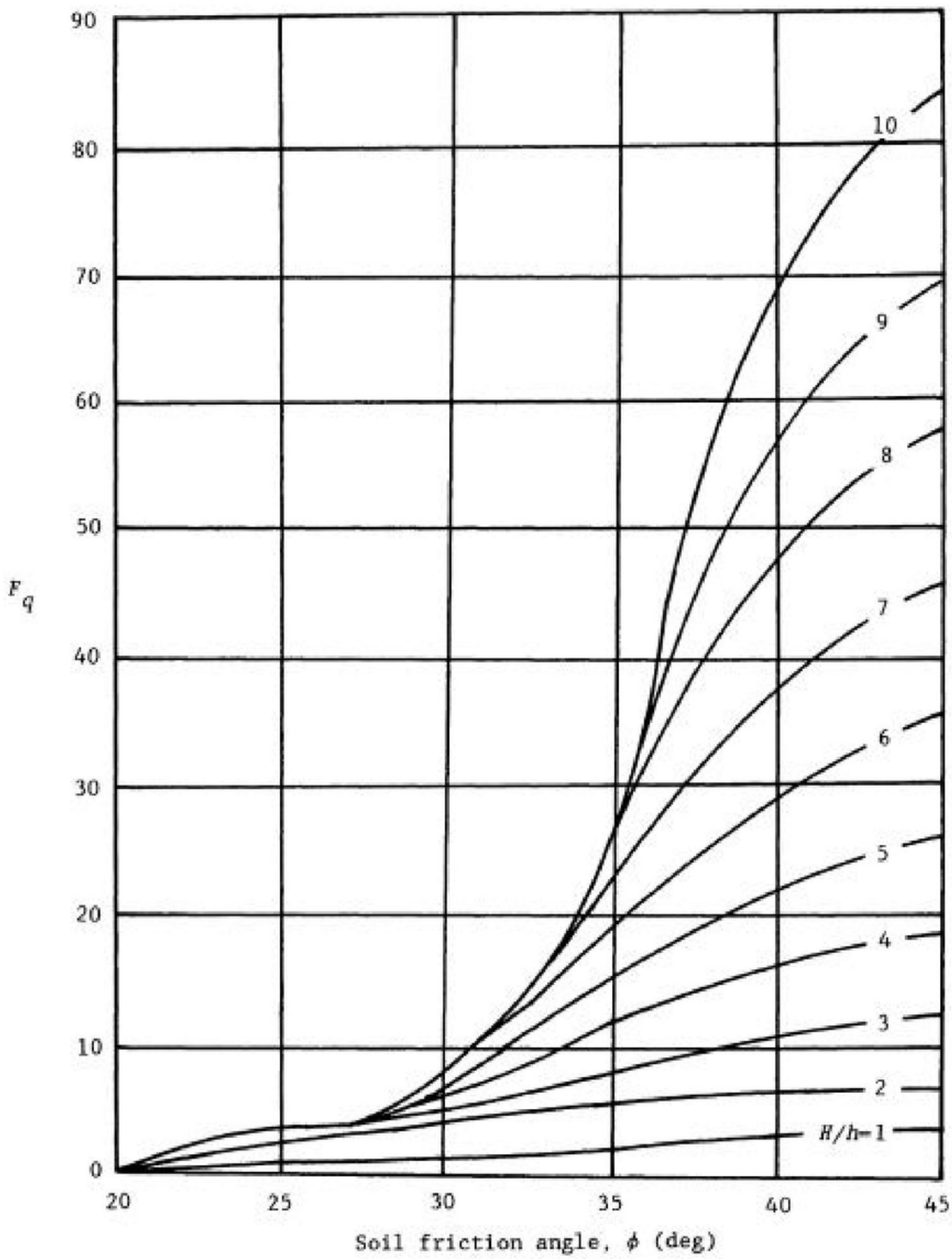

Figure 7

Plot of Fq based on Saeedy's Theory

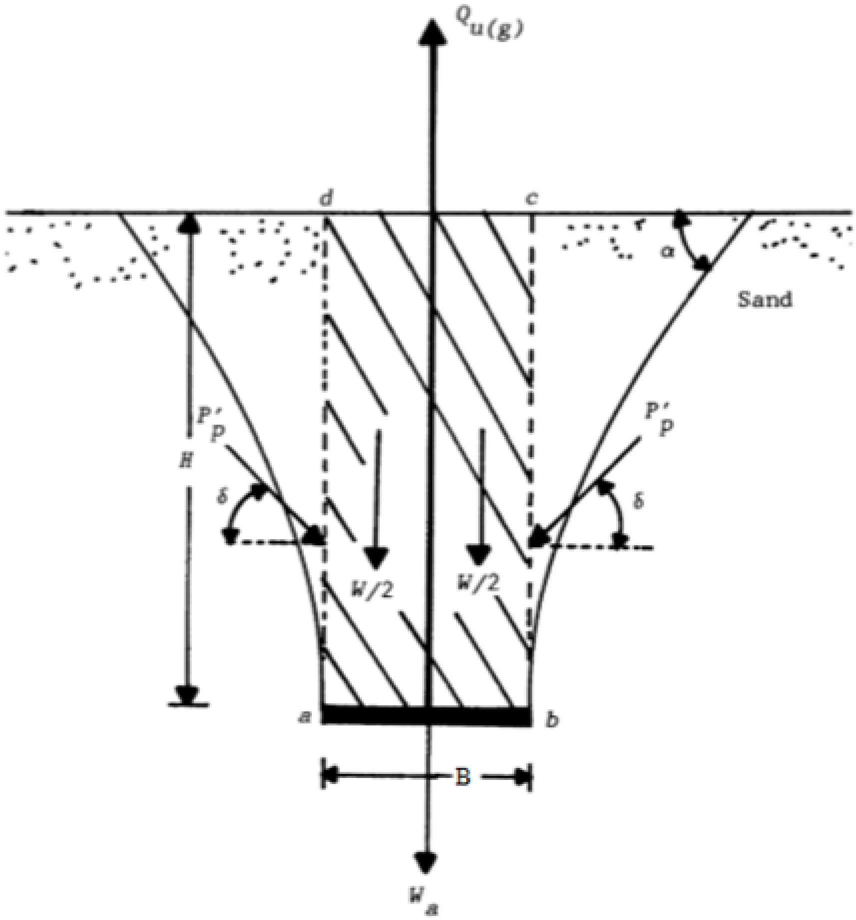

Figure 8

Forces and failure according to Meyerhof & Adam’s Theory.

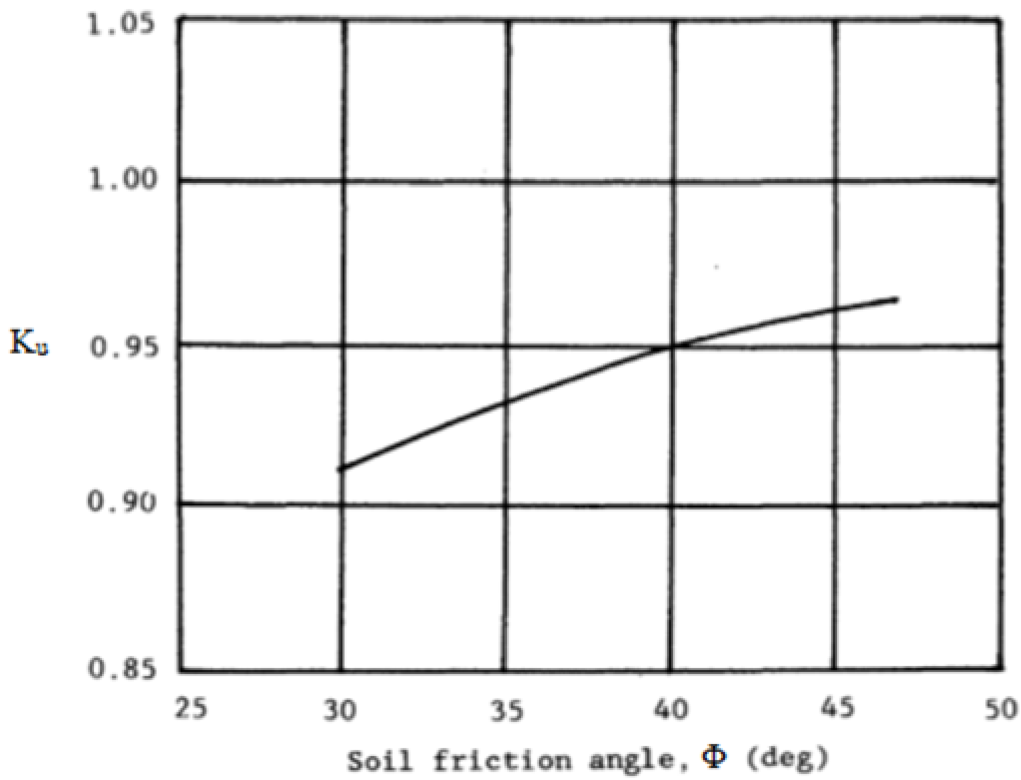

Figure 9

Variation of K_u with soil Friction Angle Φ.

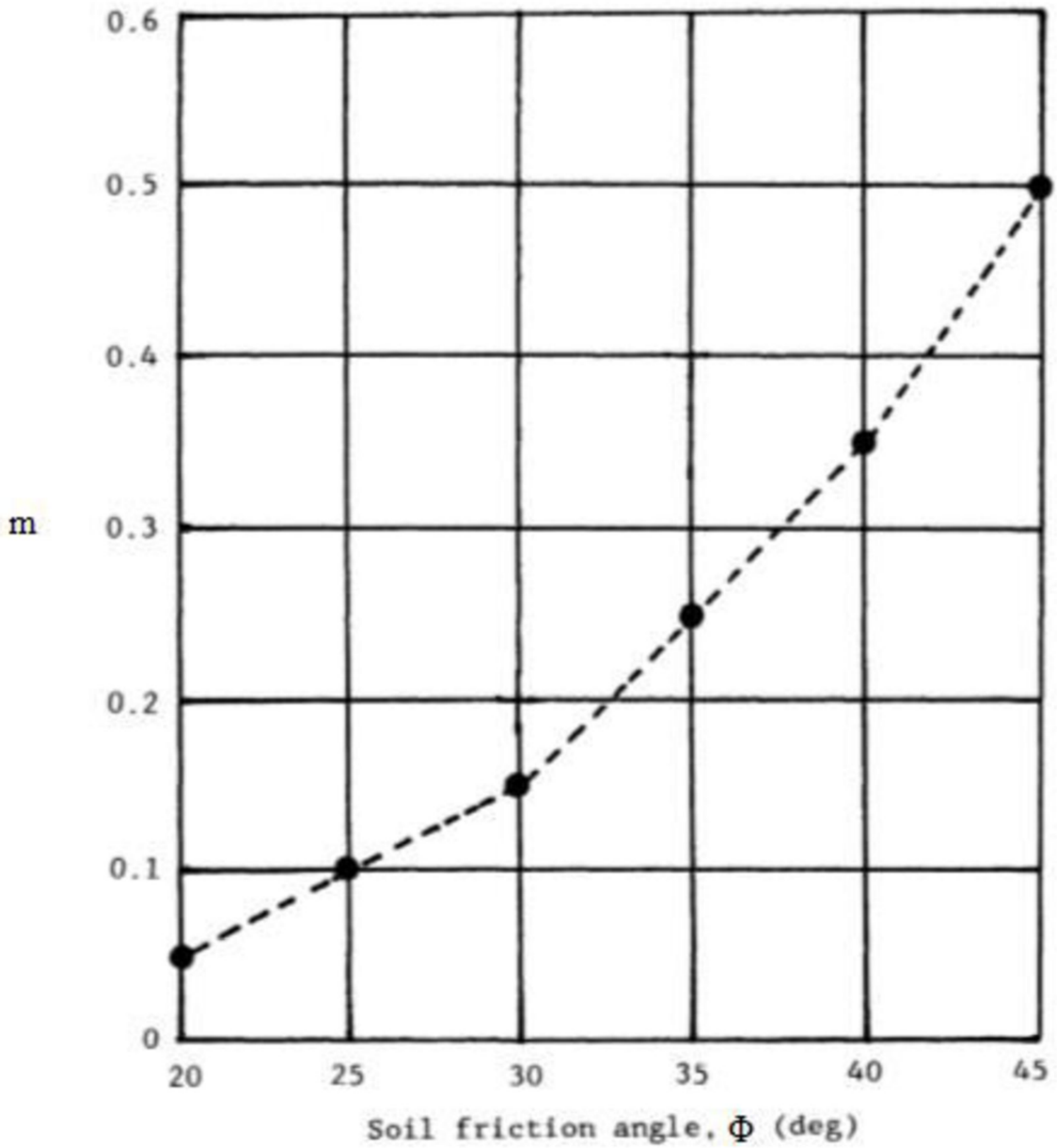

Figure 10

Variation of m with Soil Friction Angle Φ.

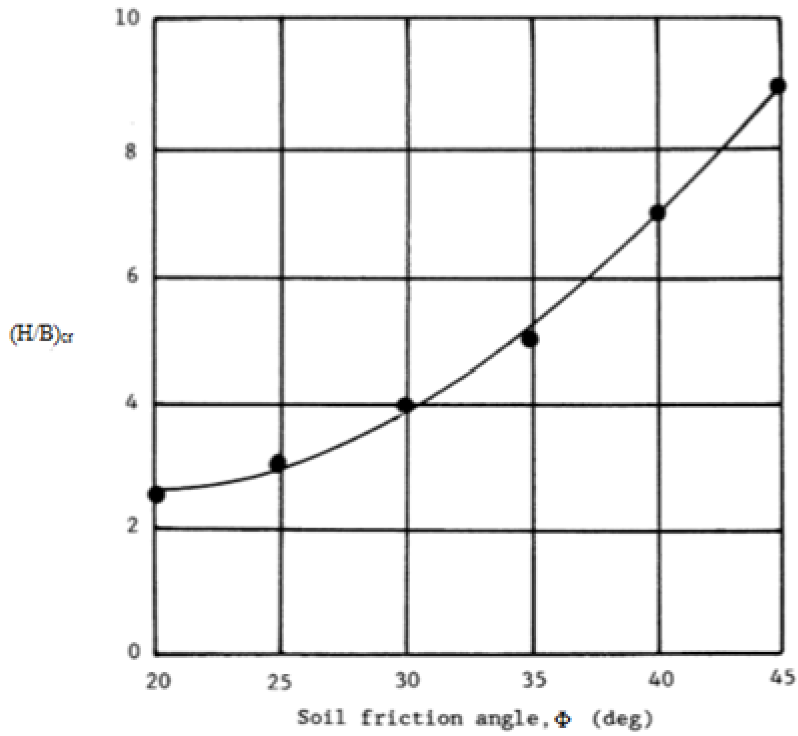

Figure 11

Variation of $(H/B)_{cr}$ with Soil Friction Angle Φ for Square and Circular Anchors.

Figure 12

Assumption surface in sand for a Circular Horizontal Plate Anchor-Veesaert and Clemence's theory (1977).

Figure 13

Variation of Fq for Shallow Circular Anchors.

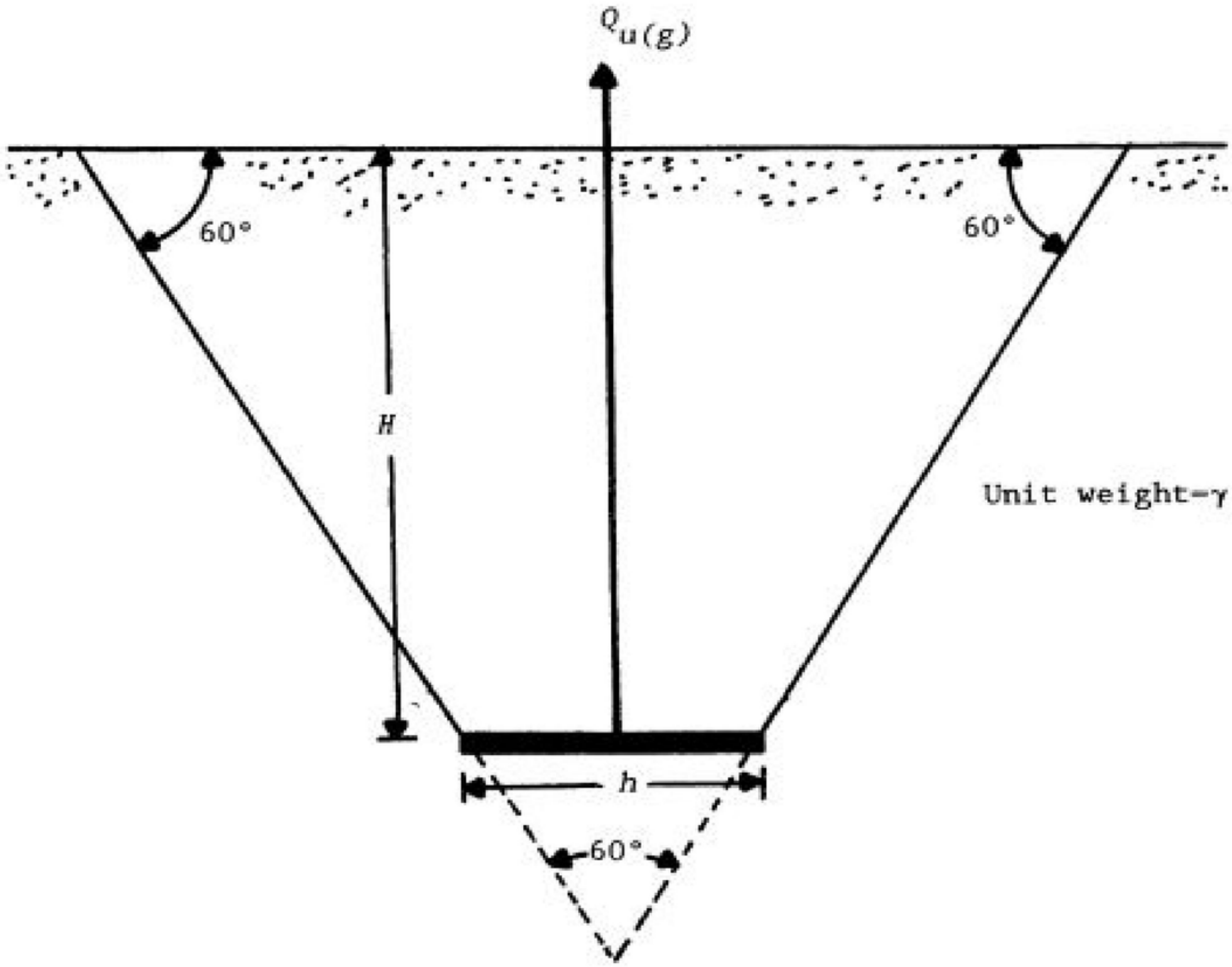

Figure 14

Downs & Cheiurzzi's Truncated Cone.

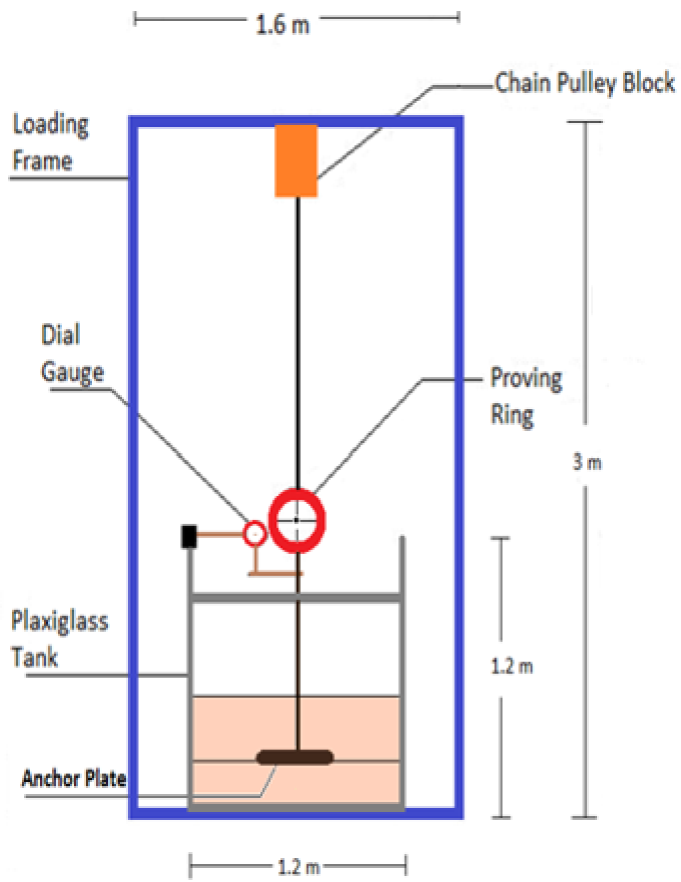

Figure 15

Schematic Diagram of Test set-up.

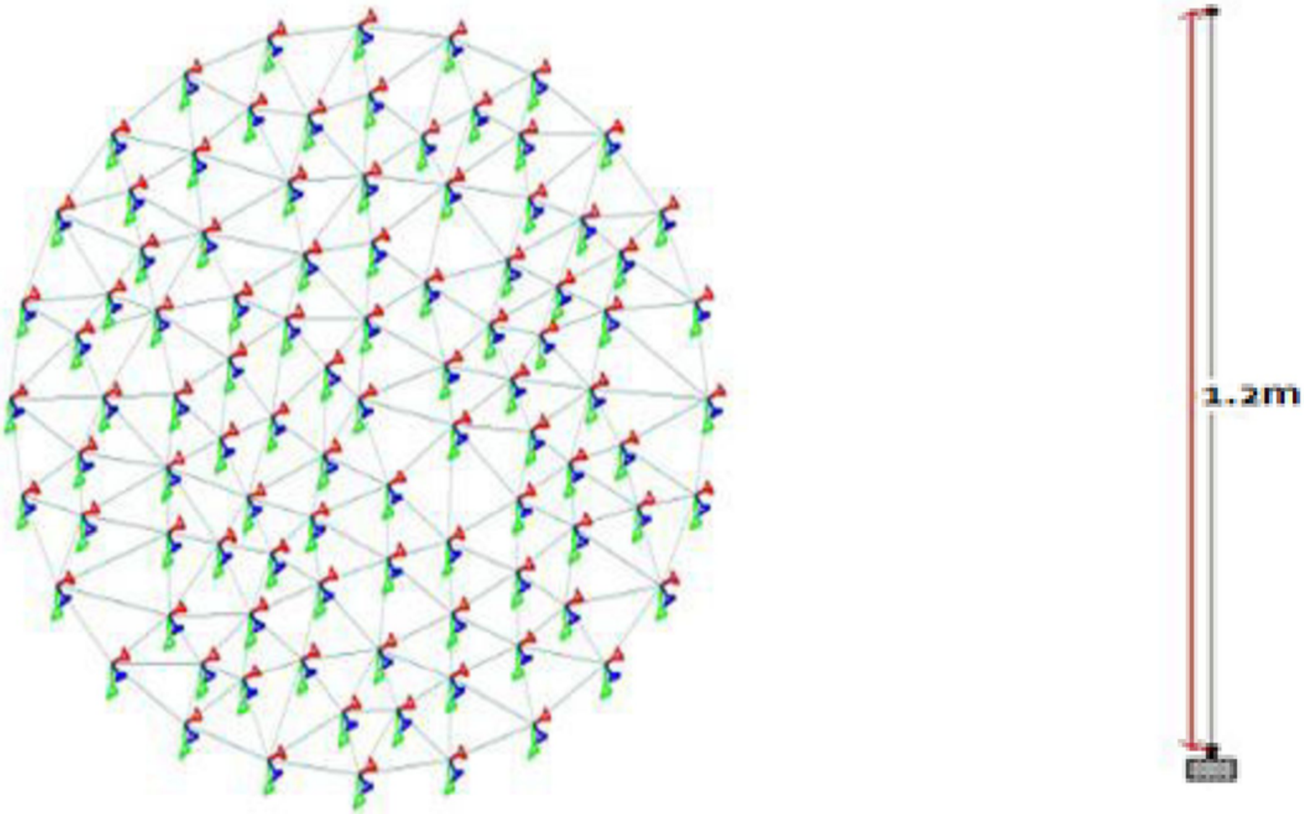

Figure 16

Anchor Plate with Rod Design in Staad Software.

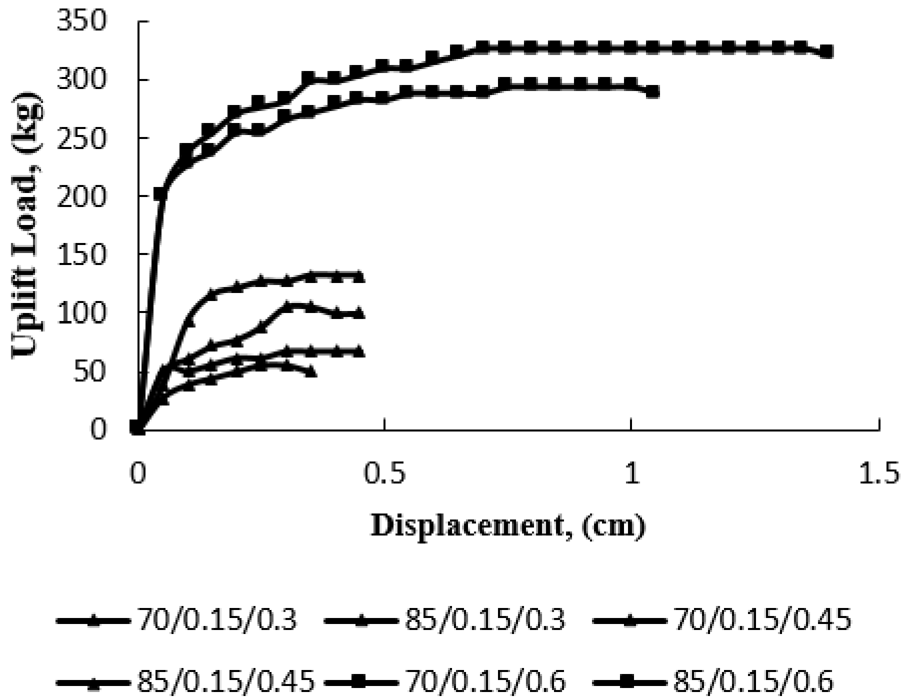

Figure 17

Load v/s Displacement for **15cm** Plate with All Relative Densities and Embedment Depths.

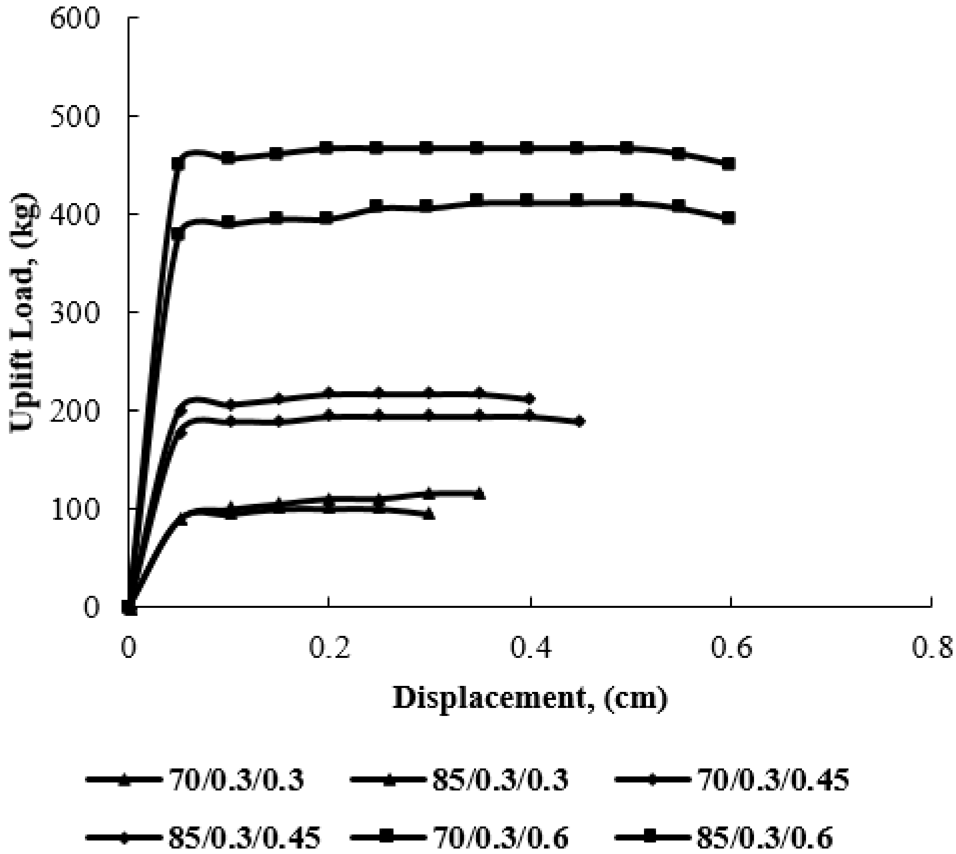

Figure 18

Load v/s Displacement for **30cm** Plate with All Relative Densities and Embedment Depths.

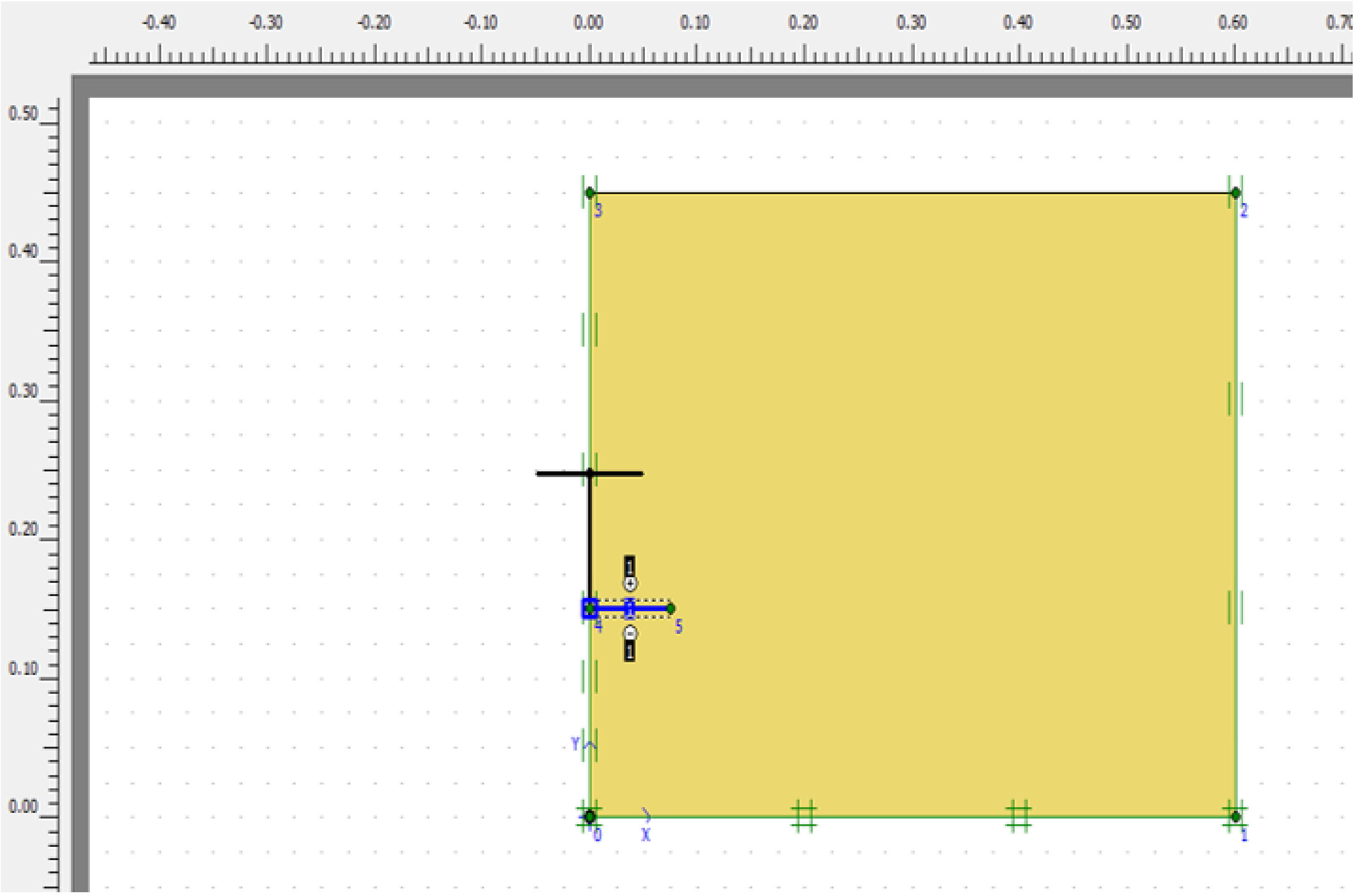

Figure 19

Axisymmetric Modelling of Anchor Plate

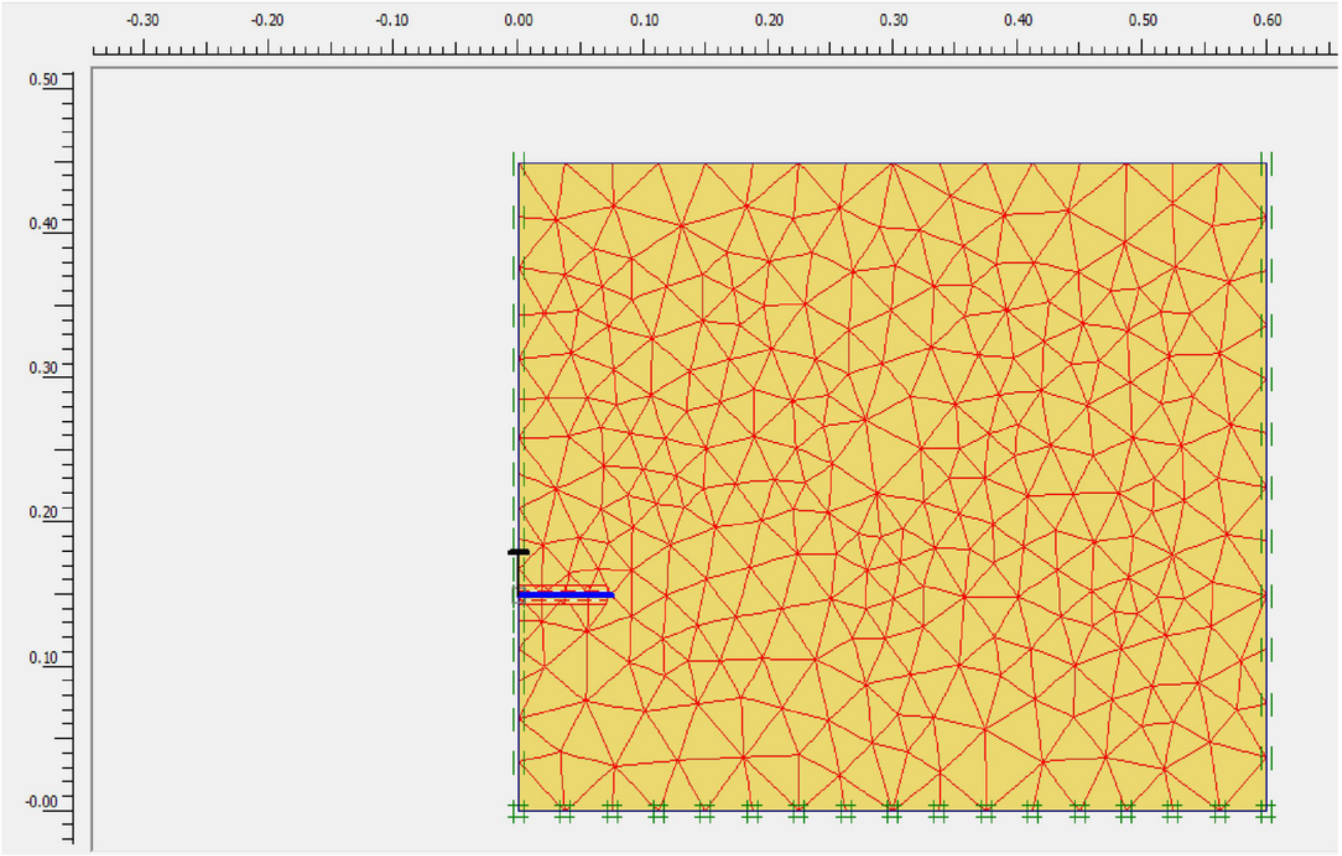

Figure 20

Mesh Generation

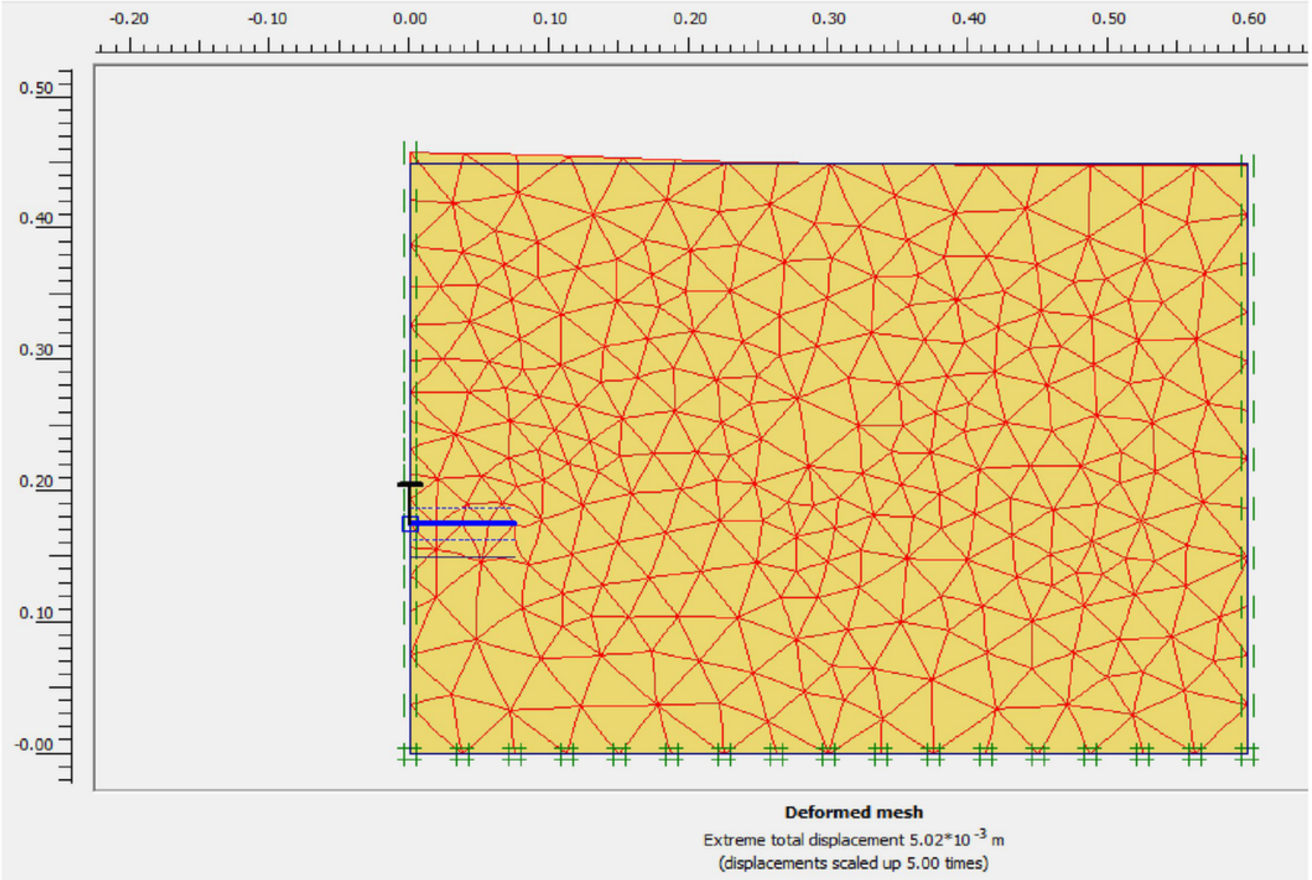

Figure 21

Displacement as Output

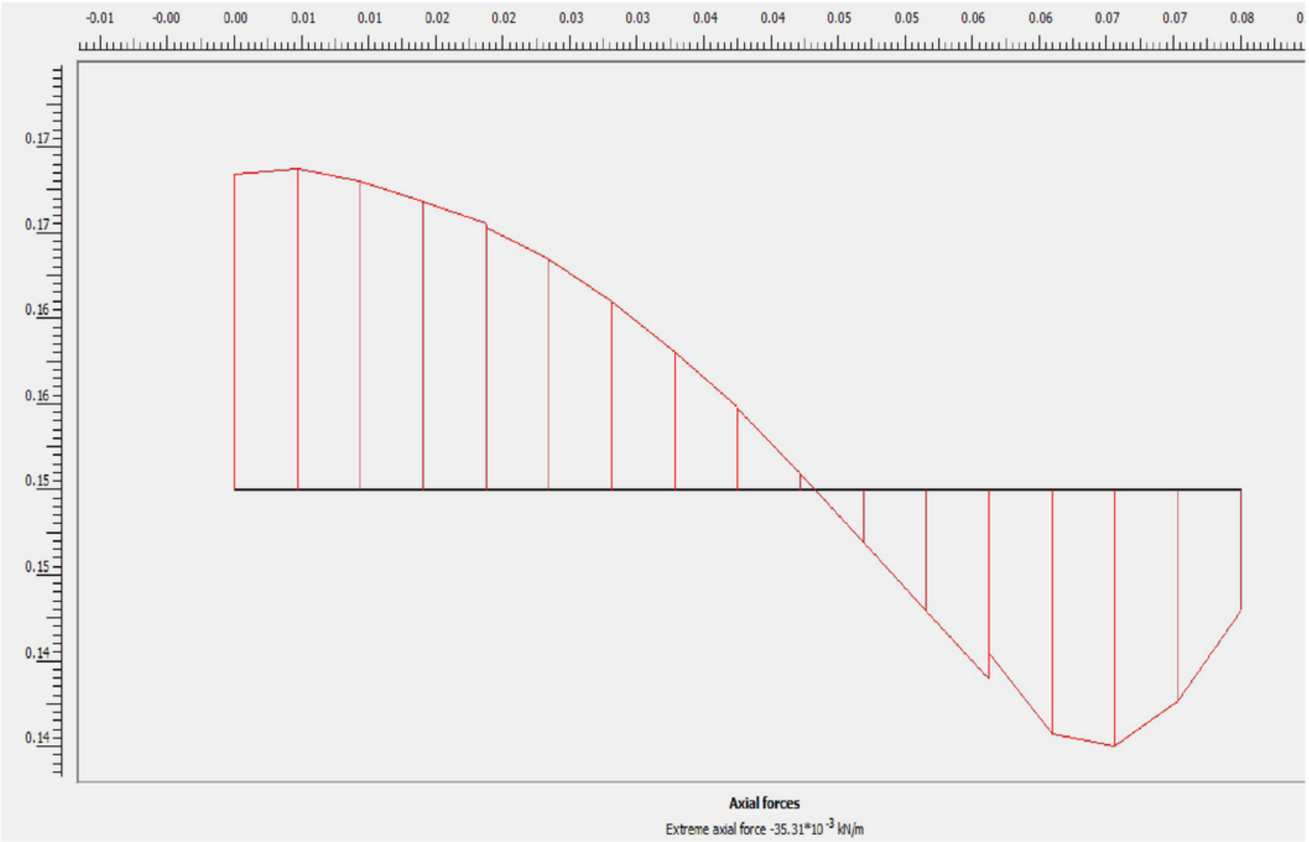

Figure 22

depicts the uplift force (output) on anchor plate.

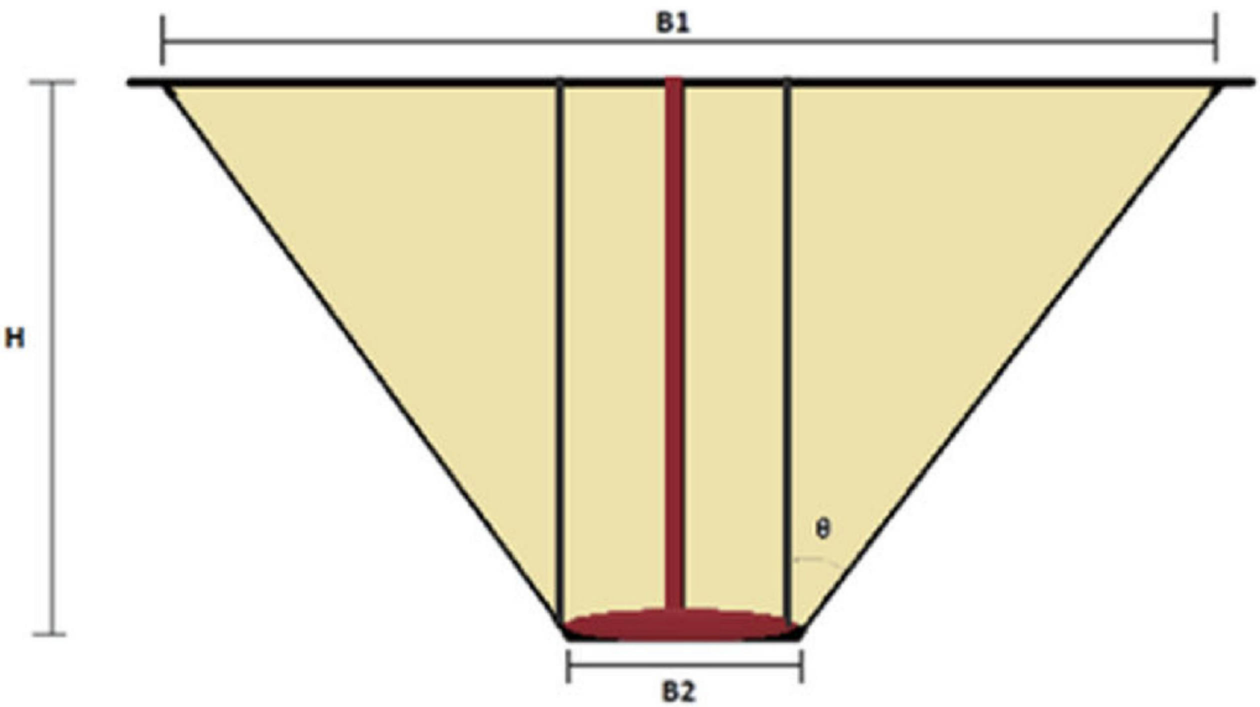

Figure 23

Proposed Angle .

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 2SPECIFICGRAVITY.xlsx
- 3RELATIVEDENSITY.xlsx
- 4DST.xlsx
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- 7ANALYTICALPULLOUTTESTAutosavedAutosavedAutosaved1.xlsx
- 7ANALYTICALPULLOUTTESTAutosavedAutosavedAutosaved.xlsx
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- 9GRAPHSOFALLMETHODSCOMBINEFORDIFFEREntmodifiedforrsquare.xlsx
- 10PROPOSEDANGLE.xlsx
- ALLMETHODSCOMBINEFORDIFFERENTEMBEDMENTRATIO.xlsx

- ALLTESTOBSERVATIONTABLE.xlsx
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