OPTIMIZATION OF UPLIFT CAPACITY OF TRANSMISSION TOWER FOUNDATIONS

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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The above candidate has carried out research for the Masters dissertation under my supervision.

Prof. H.S. Thilakasiri

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ABSTRACT

Transmission tower lines using lattice towers and concrete foundations are the common practice in most of the countries all over the world. A significant amount of the cost of the transmission tower line is spent for the tower foundation construction.

Uplift capacity of transmission tower foundation is determined based on the assumption that, the uplift force is resisted by the weight of the footing and the weight of the soil inside the volume of inverted frustum. Hence, the uplift capacity of the foundation is a major aspect of determining the dimensions of the tower foundation. However, the values of the frustum angle seem to be arbitrary and the failure pattern is more likely to be varied from the assumed pattern. Apart from that, the frustum angle is unsymmetrical for the inclined loadings. Further, the estimated uplift capacity shall also be reassessed according to the failure plane variations.

As the first step of this study, a research survey was conducted on the available empirical methods of estimating the uplift capacity. Data were collected on transmission tower types and their foundation types based on different soil categories.

This report will use PLAXIS; a finite element software to analyze the uplift capacity of transmission tower foundation. A comparison between the results from the software analysis and the capacities given by empirical methods is included in the report. An evaluation on the assumptions made on frustum angle, composition of uplift capacity to determine the uplift capacity of the transmission tower foundations is also given in the report. This analysis also includes the failure patterns, uplift capacity, composition variation of uplift capacity for different types of foundations used for transmission towers. Conclusively, this will evaluate and make a recommendation on determination the uplift capacity of transmission tower foundation, assumption of the frustum angle and the composition of the uplift capacity.

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LIST OF ABBREVIATIONS

CEB	Ceylon Electricity Board
PLS-CADD	Power Line Systems – Computer Aided Design and Drafting
SAP	Structural Analysis Program
PLAXIS	Plasticity Axi-Symmetry
3D	Three dimensional
FEM	Finite element model

LIST OF APPENDICES

Chapter 1

Introduction

1.1 Background/ Survey of Previous Work

Power is the most demanding utility, as it is an essential factor for the domestic activities as well as for the industrial purposes of the country. Currently, the average per capita electricity and gross generation is continuously increasing at an annual rate of 7.6%. Therefore, the requirement of transmission line length to enhance the national grid has increased. In most cases, the foundation cost of these transmissions lines is approximately around 25-35% of the total cost of the transmission line. Hence, optimizing the tower foundation will give a great support for the advancement of the technical aspects of the transmission tower line construction.

The two ends of the transmission tower line will be a gantry and a grid substation in most cases which may located either at a power station or in selected load centers of the island. Mostly, the line route for any transmission tower line is selected through the lands which are unoccupied as dwellings. However, there are some occasions where the line is constructed through highly congested areas which are congested with dwellings and commercial buildings.

The tower positions of a transmission line are selected after the proper survey which includes the ground features, line deflection points and terrain details. Mostly PLS-CAD software is used as tower positioning software to identify the best possible solution with optimum cost. Basic Anatomy of a transmission tower is shown in Figure 1.1.

Towers are basically designed for normal condition and broken wire condition which are defined as

- Normal condition - All the conductors are strung on the tower
- Broken wire condition- One or more conductor is not strung on the tower.

Transmission tower is a lattice structure which consists of galvanized steel angle sections of tor steel and mild steel conforming to the relevant standards.

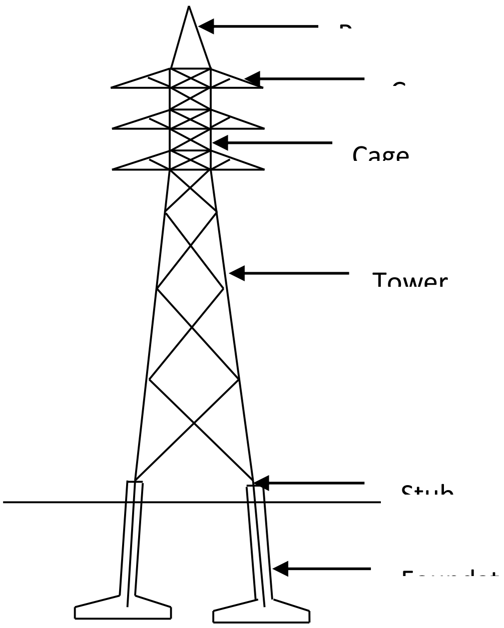


Figure 1.1 Basic Anatomy of transmission tower

Weight and wind spans are lengths specifically defined to identify the loads on the tower. The graphical interpretation of the said spans is construed in Figure 1.2. The definitions of these spans are,

- Weight span - Distance between the maximum sag points both sides of the concerned tower
- Wind span - Distances between the mid span of the both sides of the concerned tower

Maximum sag point occurs where, the conductor has its maximum downwards displacement relative to the conductor hung position on the tower.

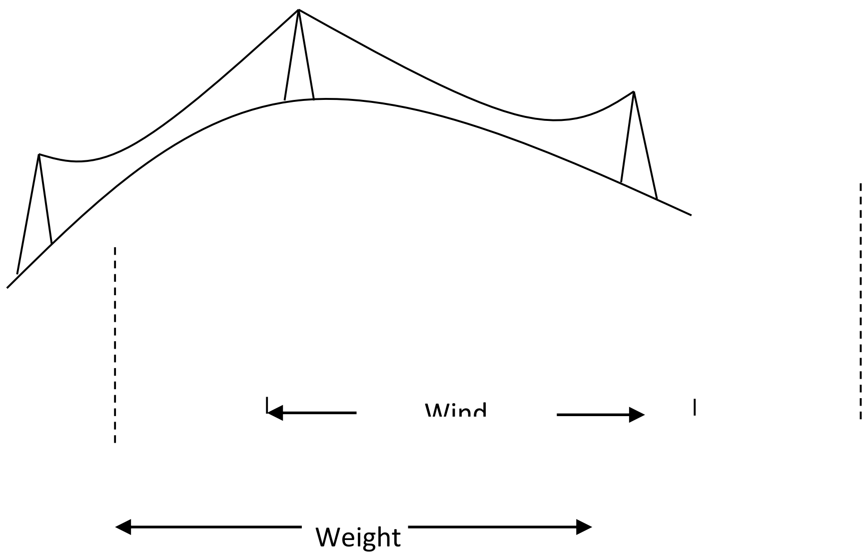


Figure 1.2 wind span and weight span of the tower at center

Tower loads considered for the analysis are dead loads, imposed loads and wind loads. However, vibrations induced on the conductor due to the wind loads are controlled by the vibration dampers, which are hung near the insulators.

1.1.1 Dead loads on tower structure

The dead loads on the tower are summarized as

- Self-weight of the lattice structure
- Self-weight of the conductors within the weight span
- Weight of the insulators, connectors and other accessories required to connect the conductor to the insulator

1.1.2 Imposed loads on tower structure

Imposed loads on tower includes

- Workmen on tower

- Pulleys used for stringing purposes
- Ropes used for lift accessories to the tower top
- Portable buckets which can be mounted on the conductor, used for the inspection of the conductor
- Temporary fixing ladders and other tools used for livewire maintenance

1.1.3 Wind loads

Wind load on tower and conductor length within the wind span are considered for the designing of tower.

Considering the above loads and conditions, towers are analyzed for numerous load combinations which arises from the construction stage to operation state. According to the current practices, towers are categorized as given in Table 1.1.

Table 1.1 Tower types used in transmission lines

Tower Type	Description	Horizontal Angle
TDL	Suspension tower	0°
TD1	Light angle tower	0° – 10°
TD3	Medium angle tower	10° – 30°
TD6	Heavy angle tower	30° – 60°
TDT	Terminal tower	0° – 45° entry on line side

The above notation is used for the easy identification of a tower type according to the deflection angle of the line at the tower, which is abbreviated as follows

- T - Tower
- D - Double circuit
- L - Deviation angle is zero

The last notation of every tower type is varied according to the deflection angle as described in the Table 1.1.

In most occasions, Finite element software is used to analyze the tower structure due to the complexity and time consumption of the analysis. Most commonly used software is PLS-TOWER, which is specifically designed for the transmission tower analysis. Although, it does not facilitate as much as PLS-TOWER, SAP2000 has also been used for tower analysis. Following reactions on tower foundation are determined through the analysis

- Axial compression force along the stub
- Axial uplift force along the stub
- Shear forces in longitudinal and transverse directions

The foundations of the transmission towers can be designed for the soil conditions of the exact tower location. However, this method seems to be expensive as it involves numerous soil tests, design and paper works. Hence, few soil categories are defined including soil types with close range of bearing properties. Then, the foundations are designed for those soil categories for each tower types. This method is less time consuming and it reduces the design and paper works. However, a soil test is conducted on each tower location to identify the exact soil conditions before the construction. Table 1.2 [1] gives the soil types selected for the design of transmission tower foundations.

Rock anchoring foundations are occupied for the S1 category, if the rock is solid without any cracks. Pad and chimney foundation is the designed for soil types S2, S3, S4 and S5, whereas a raft or pile foundations are used for the soil category S6 based on a comprehensive soil test report. Geotechnical design criteria considered for the foundation is

- Check for bearing capacity
- Check for uplift capacity
- Check for sliding
- Check for overturning

Structural design of the tower foundation consists of

- Design for bending of pad for compression and uplift
- Design for shear of pad for both direction
- Design of chimney for bending in compression and tension

Table 1.2 Soil types categorized for the tower foundation design

Transmission Towers			
Soil Type	**Allowable Bearing Capacity (kN/m2)**	**Design uplift frustum angle**	**Soil Density (kg/m3)**
S1 – Homogeneous rock	> 2000	45	2000
S2 – Fractured rock /Dense sand/gravel	> 600	30	1800
S3 – Medium dense gravel/Medium dense gravel with sand/Compact sand/Very stiff to stiff clay/Hard clay	> 200	20	1600
S4 – Loose sand & gravel/Medium dense sand/Stiff clay/Firm clay	> 100	10	1500
S5 – Soft Clay/Silt/ loose sand	> 50	-	1400
S6 – Very soft clay & silt/Peat & organic soil/Made ground or fill	-	-	-

Although, bearing capacity seems to be the critical in most types of foundations, uplift capacity becomes crucial for tower foundations in some occasions. Uplift capacity of a tower foundation is defined as the buoyant weight of the tower foundation and the soil weight of the volume included in the inverted frustum of a pyramid on the base of the foundation with sides making an angle equal to the angle of earth frustum applicable for a particular type of soil [2]. This is more elaborated in Figure 1.3. The frustum angle is defined to compensate the shear stresses along the failure planes plus the weight of the soil within the failure planes. This arbitrary value of frustum angle is used for the calculation of uplift capacity due to the unpredictability of exact failure plane for the different kind of soils. These arbitrary values of frustum angle are conclusions of vast actual and prototype testing. The concluded earth frustum angle for cohesive soils is 30° and for non-cohesive soils such as sand and gravelly soils is 20°. However, when the tower stub is pulled out with an angle to the vertical, these assumptions may vary.

It is also observed that, finite element methods are now being used to resolve these type of problems, where the exact failure planes and uplift capacities can be identified. PLAXIS is one the most commonly used software to model such problems.

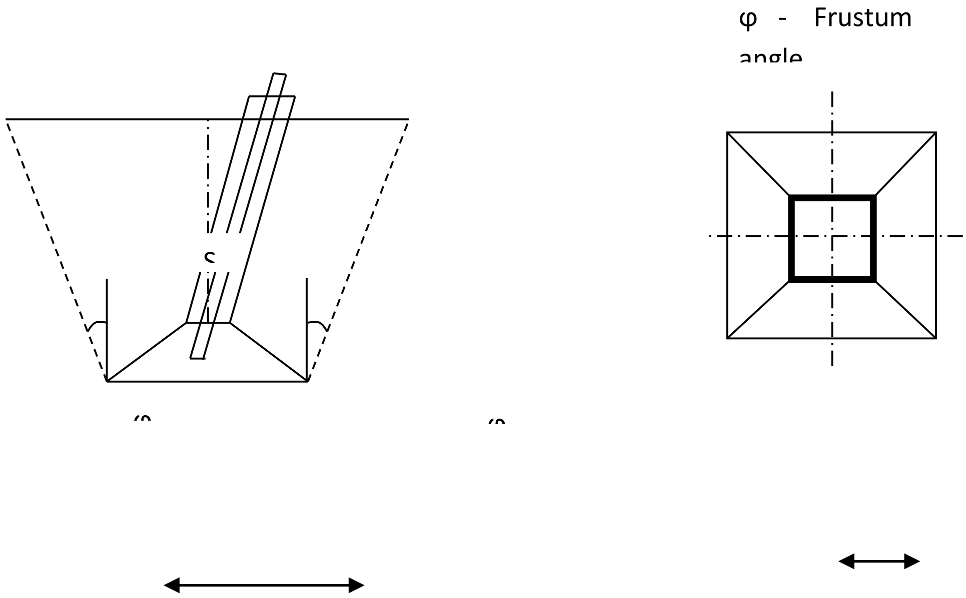


Figure 1.3 Assumed soil behavior when foundation subject to uplift

1.2. Objectives

The uplift capacity calculations for the transmission tower designs is based on a conventional method, which is used to determine the uplift capacity of the foundations subject to vertical uplift forces. However, the uplift forces acting on the transmission tower foundations are inclined with a small angle to the vertical. Hence, the effect of this inclination has to be researched. However, most uplift capacity calculation methods are developed to determine the uplift capacity of shallow foundations and enlarged piles which are subjected to vertical uplift forces. Since, the inclined angle of uplift force is within the range of 15 degrees to the vertical, the possibility of applying the methods in literature to determine the uplift capacity of transmission tower foundations has to be studied in more detail.

Hence, the objectives of this research are as follows:

- Identification of the behavior of the foundation with the variation of foundation width and friction angle, cohesion, elasticity and unit weight of soil
- Identification of actual behaviour of the transmission tower foundation when it is subject to inclined uplift forces using PLAXIS finite element modulation software.
- Compare the PLAXIS model results with empirical methods to identify the possibility of using empirical methods in calculating the uplift capacity of transmission tower foundations
- Compare the designed uplift capacities of tower foundations with the analysis results and empirical calculations
- Identifying the composition of the uplift capacity and make recommendation on method to determine the uplift capacity of transmission tower foundation

1.3. Methodology

The methodology adopted to achieve the aforementioned objectives is briefed as follows.

Literature review is focused on the areas mentioned below.

- Review on the current method used for uplift capacity calculation
- Identification of empirical methods used for calculation of uplift capacity of foundations and the basic assumptions of those methods
- Use of PLAXIS 3D to model the tower foundation.
- Identification of soil parameters suitable for the soil types as defined in Table 1.2

The analysis is started with the model verification. Then the analysis is focused on identifying the actual behavior of the foundation when the foundation is subjected to vertical and inclined uplift forces. The analysis is conducted to identify the variation of the uplift capacity with the friction angle, density and foundation width for both undercut and without undercut foundations. The foundations considered are subject to vertical uplift force and those are modelled with a vertical stub. The results were compared with the calculated capacities using empirical methods. The foundation widths which are used for this analysis are 3m, 4m, 5m and 6m. The analysis schedule is given below

- PLAXIS 3D model verification using Load-displacement curve obtained from the PLAXIS analysis and physical model
- Analysis of foundation for he variation of the foundation width for the normal and undercut foundations. The friction angle, unit weight, cohesion and elasticity of soil for this analysis are 38 degrees, $21kN/m^3$, 5kPa and 35000kPa respectively. The results are compared with the results of empirical methods
- Analysis of 5m width under and normal foundation for variation of friction angle from 29 to 38 degrees. The unit weight, cohesion and elasticity of soil for this analysis are $21kN/m^3$, 5kPa and 35000kPa respectively. The parameters used for backfill is slightly lower than above values for unit weight and elasticity. The undercut foundations are considered for this analysis. The results are compared with the calculated capacities using empirical method.
- Analysis of 5m undercut and normal foundations for the variation of cohesion of the soil. The friction angle, unit weight and elasticity of soil for this analysis are 38 degrees, $21kN/m^3$ and 35000kPa respectively. The results are compared with the results of empirical methods
- Analysis of 5m undercut and normal foundations for the variation of unit weight of the soil. The friction angle, cohesion and elasticity of soil for this analysis are 38 degrees, 5kPa and 35000kPa respectively. The results are compared with the results of empirical methods
- Analysis of 5m undercut and normal foundations for the variation of elasticity of soil from 25000kPa to 40000kPa. The friction angle, cohesion and unit weight considered are 38 degrees, 5kPa and $21kN/m^3$ respectively. These results also compared with the calculations using empirical methods.

- Analysis of 5m undercut and normal foundation for the inclination of the applied uplift force from 0 to 20 degrees where the other parameters friction angle, unit weight, cohesion and elasticity of soil are fixed for this analysis are 38 degrees, 21kN/m^3, 5kPa and 35000kPa respectively

A comparison the ultimate uplift capacity calculated using empirical formulas and the results of the PLAXIS analysis is conducted subsequently. The scheduled analysis is as follows.

- Analysis of TD1-S2 foundation using PLAXIS 3D and empirical formulas
- Comparison of the composition of the uplift capacity according to the empirical formulas, PLAXIS 3D analysis and method using assumed frustum angle
- Analysis and comparison of TD1-S2, S3, S4 and S5 foundations using PLAXIS 3D and empirical formulas for failure patterns, uplift capacity.
- Comparison of selected frustum angle for soil categories with actual soil behaviour.
- Analysis and comparison of S2 foundations for TD1, TD3 and TD6 towers using PLAXIS 3D and empirical formulas for failure patterns, uplift capacity.

Discussions and conclusions are focused on the following topics

- Appropriateness of using frustum angle for the calculation of uplift capacity of towers
- Suitability of proposed empirical equations to use for the calculation of uplift capacity of tower foundations
- Composition of the uplift capacity of transmission tower foundation.

Chapter 2

Literature Review

2.1 Uplift capacity calculation method using assumed frustum angle

The method used for this calculation is based on the concept that the uplift force is resisted by the self-weight of the foundation and weight of the soil of the frustum cone above the foundation [2]. However, the friction developed in the failure plane is not considered in this method. Instead of that, it is assumed the frictional resistance is compensated by the weight of the soil within cone as shown in Figure 1.3. Although this method assumes the cone is forming symmetrically around the foundation according to the frustum angle, it might differ in actual scenario due to the uplift force being inclined to the foundation in transmission towers.

2.2 Uplift calculation methods in Literature

However, there are several methods of calculating uplift capacity of foundations, which can be divided into mainly to three categories as mentioned below [3].

- Cone method
- Earth pressure method
- Semi empirical method

2.2.1 Cone method

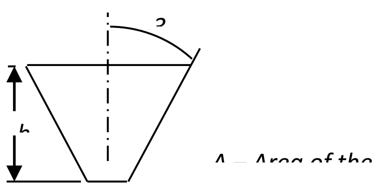
This method assumes that the failure of foundations subject to uplift force occurs along a plane inclined at a defined angle known as frustum angle. Different definition for the frustum angle is proposed by various researchers as mentioned below.

2.2.1.1 Dewberry method

Dewberry [4] has developed a graphical method to determine the uplift capacity of circular ground anchors. According to the assumed conical shape as shown in Figure 2.1, it was calculated the volume (V) of the soil as shown in the Equation [2.1].

$$V = Ah + A^{0.5}h^2 + 0.35h^3 \qquad [2.1]$$

The anchor holding capacity is determined by multiplying this volume by a factor K_d[4], which is defined for different soil classes is attached Appendix 2. A and h are measured in square inches and feet respectively.



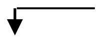


Figure 2.1 Assumed failure plane in Dewberry method

2.2.1.2 Balla's method

Balla [5] proposed a method to calculate the uplift capacity for circular shallow foundations of which the depth to the width ratio of the foundation is lower than 6. This method is based on assumed parabolic failure surface rather than a conical failure surface as shown in Figure 2.2, the curvature being a function of internal friction angle of soil.

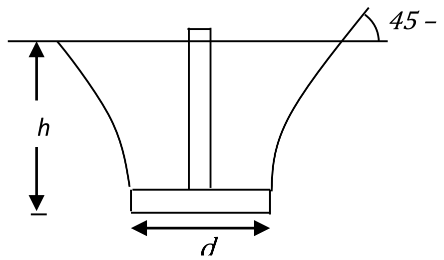


Figure 2.2 Assumed failure plane for Balla method

Balla [5] has added the cohesive and friction forces acting along the failure surface to the uplift capacity as well, which is a variation form the traditional cone method. Calculation formula for weight of soil within failure plane (W_s) and friction and cohesive resistance developed along the failure plane (Q_f) is given in Equation [2.2].

$$W_s + Q_f = h^3\gamma B_1 + h^2 c B_2 \qquad [2.2]$$

B_1 and B_2 [5] are value derived as function of internal friction and cohesion of soil and depth to the width ratio of foundation as given in Appendix 3. γ is the unit weight of the soil.

Balla [5] has proved close correlation between laboratory tests and theoretical values obtained by the above equation for sandy soils. Photographs of his tests shown that, the intersection of failure plain and the ground surface is at an angle of $45^{\circ} - \varphi/2$ to the horizontal.

Paterson and Urie [6] also implemented some full-scale test on inverted mushroom type tower foundations made of concrete for sandy and clayey soils. The results are more agreed with Balla's theoretical value for sandy soils. However, very poor correlation was found for clayey soils.

Flucker and Teng [7] states that, the Balla's proposal may overestimate the uplift capacity, considering the failure is progressive and the cohesion and friction is fully effective only in limited zone at a given time.

However, the advantage of Balla's method is the correlation of uplift capacity for soil properties rather than arbitrary parameters.

2.2.1.3 Matsuo and Tagawa cone method

Matsuo and Tagawa [8] introduced a modification for cone method applicable to circular footings for cohesion less soils as given in Equation [2.3]. The depth to the width ratio of the foundation is restricted to below 10 for the application of this method. Assumed failure plane for this method is given in Figure 2.3.

$$P_{max} = W_a - \gamma V_3 + \gamma R^3 K_1 (h_2/R)^{K_2} + cR^2 K_3 (h_2/R)^{K_4} \qquad [2.3]$$

where

P_{max}	=	Uplift capacity
W_a	=	weight of anchor
V_3	=	volume of footing
γ	=	unit weight of soil
c	=	unit cohesion of soil

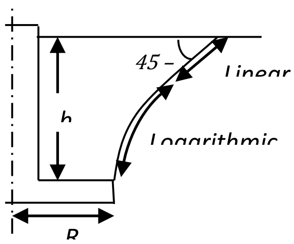


Figure 2.3 Configuration of Matsuo and Tagawa method

K_1,K_2, K_3 and K_4 [8] are factors depending on the scaled depth of burial and internal friction angle as given in Appendix 4. Calculations show a good relation between this method and Balla's test results.

2.2.1.4 Mariupol'skii cone method

Mariupol'skii [9] proposed a variation to the cone method as elaborated in Figure 2.4 and Equation [2.4]. This method is applicable to the foundations having depth to the width ratio of less than 6.

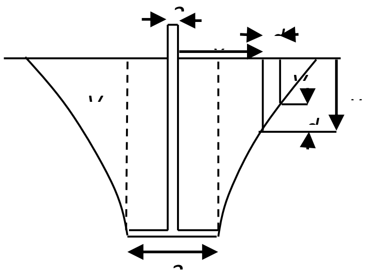


Figure 2.4 Failure pattern of Mariupol'skii proposal

$$P_{max} = W_a + \pi(R^2 - R_0^2)\frac{\gamma h\left[1 - (R_0/R)^2 + K_a tan\varphi(h/R)\right] + 2Sh/R}{1 - (R_0/R)^2 - \mu h/R}$$

where

S	=	unit shear strength of soil
K_a	=	coefficient of active earth pressure
W_a	=	weight of foundation

μ	=	dimensionless function of the angle of internal friction derived from the results of anchor tests made in the laboratory and field given in Appendix 5 [9]

The values obtained from the proposed equation is similar to the Balla's test results for cohesionless soils. The failure in cohesive soil is progressive. Therefore, the cohesive forces will not be developed over the entire failure plane simultaneously, as assumed for the equation.

Although the aforementioned methods are proposed for the circular anchors, the possibility of using the method for tower foundations is observed in the analysis by using an equivalent diameter for the tower foundations.

2.2.1.5 Mayerhof and Adams method

Mayerhof and Adams [10] proposed another cone method calculating the uplift capacity of square foundations as shown in equation [2.5].

$$Q_f = \gamma D^2(2SB + L - B)K_u tan\varphi \qquad [2.5]$$

where

S	=	$1 + m(D/B)$
D	=	Depth to the foundation top
B	=	Breadth of foundation
L	=	Length of foundation
m	=	Shape factor coefficient
K_u	=	Uplift coefficient

The uplift coefficient and shape factor coefficient [10] are defined to correlate with the friction angle of the soil. The said correlation is given in the Appendix 6.

2.2.2 Earth pressure method

Earth pressure method is another method of determining the uplift capacity of anchors, which also known as friction cylinder method, Swiss formula, or Frohlick Majers' procedure. This method considers the failure plane is vertical and similar to the cross section of the footing as shown in Figure 2.5. The pullout capacity is correlated to the frictional force along the vertical failure plane.

The basic concept of this method is, the resistance to the uplift force is given by the weight of the anchor, weight of the soil within failure plane and the frictional force developed along the failure plane. Further, most researchers have correlated the frictional force along the failure plane to the horizontal earth pressure along the failure plane. The calculation methods which are introduced by different researchers, based on the said concept to determine the uplift capacity are listed below. These methods are used for the foundations having depth to width ratio less than 6.

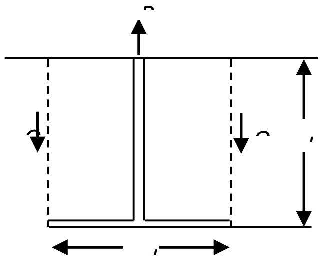


Figure 2.5 Assumed failure plane in Earth pressure method

2.2.2.1 Mueller method

Mueller [7] related the frictional force along the failure plane to the vertical earth pressure as given in Figure 2.6 and Equation [2.6].

$$Q_f = \left[\frac{Kh\gamma}{2} 2h(a+b)tan\varphi + 2(h-h_2)(a+b)f_c\right]$$

where

f_c	=	Coefficient of friction between soil and concrete
K	=	Lateral coefficient of earth pressure
φ	=	Internal friction angle of soil
γ	=	Unit weight of soil

The coefficient of earth pressure at rest K_0 is suggested for different kind of soils rather than using of K_p as proposed initially. The suggested values for f_c and K_0 [7] are given in Appendix 7.

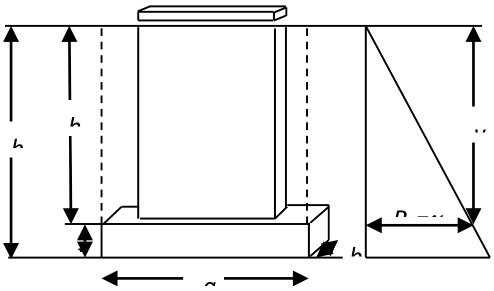


Figure 2.6 Configuration of method proposed by Mueller

2.2.2.2 Mors method

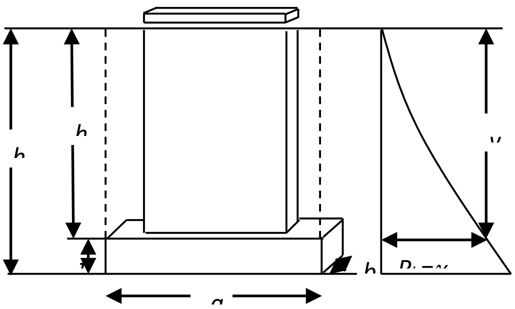


Figure 2.7 Proposed stress distribution by Mors

Mors [11] suggested that K_p generally gives overestimation of failure load. Hence, he concluded, the horizontal earth pressure equals to the passive earth pressure only at the base of the footing. Then, he proposed to distribute that passive earth pressure along the failure plane according to a function which is shown in Figure 2.7, which is incorporated to the calculation of coefficient of passive earth pressure K_p as given in Equation [2.7].

$$K_p = \frac{2}{j+1} tan^2(45° + \varphi/2)$$

This value for K_p is used in equation [2.6], for the value of K. Empirical values for j [11] is given in Appendix 7, which is defined according to the footing type and soil conditions.

2.2.2.3 Motorcolumbus method

An empirical modification is proposed by Motorcolombus [11] for earth pressure method based on numerous full-scale tests. It was found that, the frictional force is not linearly varied with the depth. For instance, it was stated, if the depth of the foundation is doubled, the friction force would only be increased by 20-25%. It was also stated that, frictional forces reduced by 50% than the normal values for soils below water table. The proposed empirical modification is given in Equation [2.8].

$$P_{max}n = W_s + W_a + C_5 h^x \quad [2.8]$$

C_5 is defined as $4aK$, where K is coefficient of earth pressure. x has a constant value of 1.52. n is safety factor as required. W_s and W_a are weights of soil and foundation respectively. The mentioned method is proposed for rectangular foundations and considered in the analysis for the possibility of using them for calculating the uplift capacity of tower foundations accurately.

2.2.3 Semi-empirical method

Semi-empirical methods are proposed after observing numerous model tests and full scaled tests.

2.2.3.1 Baker and Kondner method

Baker and Kondner [12] have confirmed the uplift capacity depends on depth to the width ratio of foundation by conducting a thorough study on model circular anchors on sand. The proposed equation to determine the uplift capacity is given in Equation [2.9].

$$P = C_1 h d^2 \gamma + C_2 h^3 \gamma \quad [2.9]$$

C_1 and C_2 [12] are constants relate to internal friction angle and relative density which has values of 3.0 and 0.67 respectively. This method can also be used for shapes other than the circular by calculating equivalent diameter. However, it was observed the pullout capacity is higher than their recommendation and Balla's equation by full scale verification tests on belled anchor in sand of depth to the width ratio of 5.3.

2.2.3.2 Turner method

Turner [13] formulated an empirical equation to calculate uplift capacity of ground anchors based on the anchor dimensions and shear strength of the soils after observing about 50 tests. He proposed two equations for two classes of foundations according to the depth to the width ratio of foundations as given in Equation [2.10] and [2.11].

For the foundations with $h/d < 1.5$

$$P_{ult} = 2.1 S^{0.5} (h/d)^2 (d^2 - D_0^2) \quad [2.10]$$

For the foundations with $h/d \geq 1.5$

$$P_{ult} = 5.8 S (d^2 - D_0^2) \quad [2.11]$$

where

P_{ult}	=	uplift capacity
S	=	unit shear strength of soil
h	=	anchor embedment depth
d	=	anchor base diameter
D_0	=	shaft diameter

Most of the values computed by the proposed method are relatively close with the actual results, but conservative.

2.2.3.3 Biarez and Barraud method

Biarez and Barraud [14] method is based on the shear strength of the soil acting along the failure plane defined for various soil conditions as indicted in Figure 2.8. Extensive model testing and series of field testing was conducted in different soil conditions to determine the calculation method as mentioned in Equation [2.12].

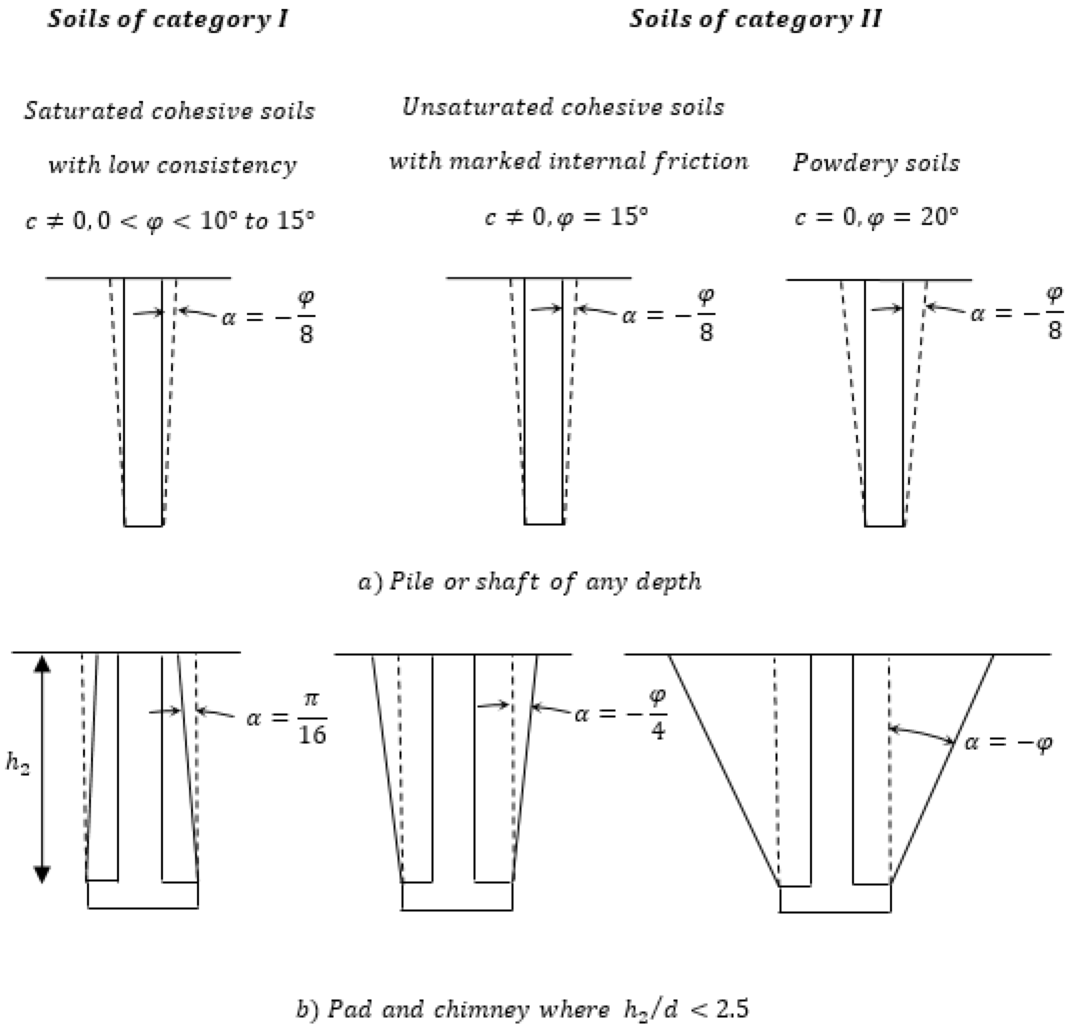


Figure 2.8 different soil conditions defined for Biarez and Barraud method

$$P_{ult} = A_1[cM_c + \gamma h_2(M_\varphi + M_\gamma) + qM_q] + W_a \qquad [2.12]$$

where

P_{ult}	=	uplift capacity
A_1	=	circumferential area of foundation

c	=	unit cohesion
γ	=	unit weight of soil
h_2	=	depth to the top of the foundation
W_a	=	weight of soil within fictitious pile form within fictitious pile as indicated in Figure 2.8
q	=	surcharge load on soil
M_c	=	cohesion coefficient as given in equation [2.13]
M_φ	=	friction coefficient as given in equation [2.14]
M_γ	=	gravity coefficient as given in equation [2.14]
M_q	=	overburden coefficient as given in equation [2.15]

$$M_c = M_{c0}[1 - 1/2(tan\alpha)(h_2/R) \quad [2.13]$$

$$\left(M_\varphi + M_\gamma\right) = \left(M_{\varphi 0} + M_{\gamma 0}\right)[1 - 1/3(tan\alpha)(h_2/R) \quad [2.14]$$

$$M_q = M_{c0}(tan\alpha + tan\varphi)[1 - 1/2(tan\alpha)(h_2/P) \quad [2.15]$$

where

R	=	radius of foundation
P	=	periphery of foundation
α	=	angle of shear plane as shown in Figure 2.8

Values for $M_{c0}, M_{\varphi 0}$ and $M_{\gamma 0}$ [14] are indicated in Appendix 8. Coefficients for the unit weight and overburden surcharge also given in this equation. This method can be used for shaft anchors, belled anchors and simple plates.

The methods listed in semi-empirical method are used for the analysis of tower foundations for uplift capacity to compare the results with the PLAXIS analysis.

2.3 PLAXIS Software

PLAXIS 3D version 2013.01 [15] is used to model the transmission tower foundations to identify the soil behaviour when the foundation subjects to uplift force. This is a sophisticated software having the facility to model different kind of soil behaviour using various soil models as mentioned.

2.3.1 Soil element models

2.3.1.1 Linear-elastic model

Hooke's law of isotropic elasticity is based for this model. This model is used to model stiff volumes of soils, such as concrete elements or rock formations, rather than model normal soil. This model need the basic elastic elements Poisson's ratio and Elastic modulus (E).

2.3.1.2 Mohr-Coulomb model

The linearly elastic perfectly plastic Mohr-Coulomb model requires five soil parameter inputs, Poisson's ratio and Elastic modulus (E) for soil elasticity, internal friction angle and cohesion for soil plasticity and soil dilatancy. This model represents "first order" approximation of soil behavior, a constant stiffness is estimated for each layer or stiffness increase linearly with the depth.

2.3.1.3 Soft soil model

This is a Cam-Clay type model use to model the primary consolidation of normally consolidated clay type soils. The basic assumptions of the Cam-Clay model are the soil is isotropic, elasto-plastic, deforms as continuum and is not affected by creep. The stiffness of the model is defined using λ and κ represents slope coefficient for the virgin consolidation and swelling lines respectively.

2.3.1.4 Hardening soil model

This model is defined using friction angle, cohesion and dilatancy and stiffness is defined more accurately using triaxial stiffness, triaxial unloading stiffness and oedometer loading stiffness. This model also accounts for stress-dependency of stiffness moduli which means that all stiffnesses increase with the pressure other than to the Mohr-Coulomb model. Apart from the above, this model also facilitates to consider the over-consolidation ratio of the soils.

2.3.1.5 Soft soil creep model

Soft soil creep model accounts for creep and stress relaxation rather than hardening soil model also known as secondary consolidation which is most dominant in soils like organic soils. This model is mostly used for the estimation of settlement of foundations, embankments or other relevant structure. This model also facilitates to model the over-consolidation ratio. Apart from the above software also has the facilities to develop any user defined soil models as it required.

2.3.2 Calculation procedure

The equations of finite element analysis become non-linear, when the soil plasticity involves in the calculations. Therefore, these types of problems need to be solved in a series of calculation steps. Solution algorithm and choice of calculation step size are the important aspects for this calculation. The equilibrium error for each calculation step is successively reduced using series of iterations. This iteration procedure is based on accelerated initial stress method. PLAXIS 3D program has an automatic load stepping procedure for the solution of non-linear plasticity problems. This automatic load stepping calculation procedure is controlled by number of calculation and iteration procedure control parameters as described following section 2.3.2.1, 2.3.2.2 and 2.3.2.3.

2.3.2.1 Calculation steps

This parameter defines the number of steps to be performed in a particular calculation phase. The number of steps is defined assuming the specific load or collapse load will be reached within this calculation steps. However, this will be chosen according to the intended outcome of the PLAXIS model.

2.3.2.2 Tolerated error

In most non-linear analysis which uses finite number of calculation steps, there will be a drift form the exact solution as shown in Figure 2.9. A solution algorithm ensures that the equilibrium errors both locally and globally remains within the acceptable bounds. This error limits are closely related to the "tolerated error" in PLAXIS 3D FEM software. The value of tolerated error can be predefined. This value is chosen as 0.01 for the general calculations, which will give more accurate results. However, this value can be changed according to the accuracy requirement and the nature of the problem.

2.3.2.3 Arc-length control

The reliable collapse loads for load controlled calculations are obtained by the Arc-length control procedure.

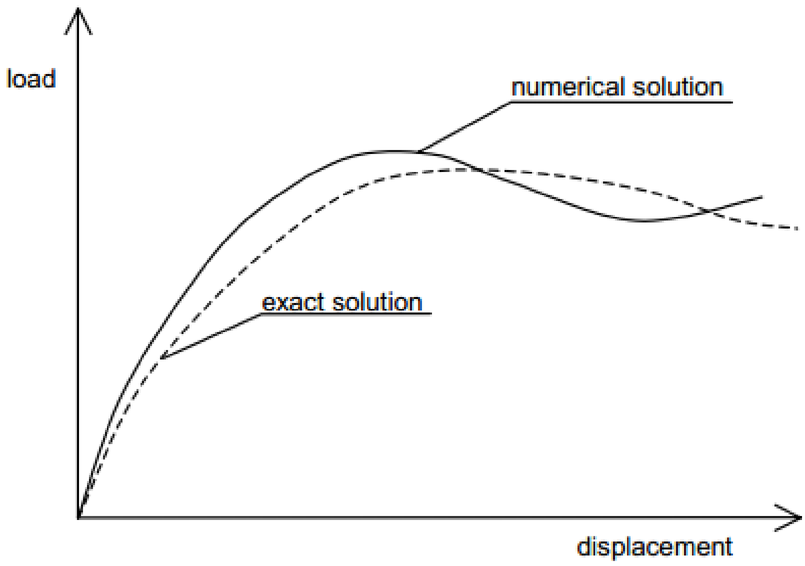


Figure 2.9 Numerical solution vs exact solution

The difference when arc-length control is applied and not applied is given in Figure 2.10. The algorithm will not converge with the load-displacement curve, if the arc-length control is not applied as shown in Figure 2.10(a). However, this will converge when the arc-length control is applied and will give the collapse load as shown in Figure 2.10 (b).

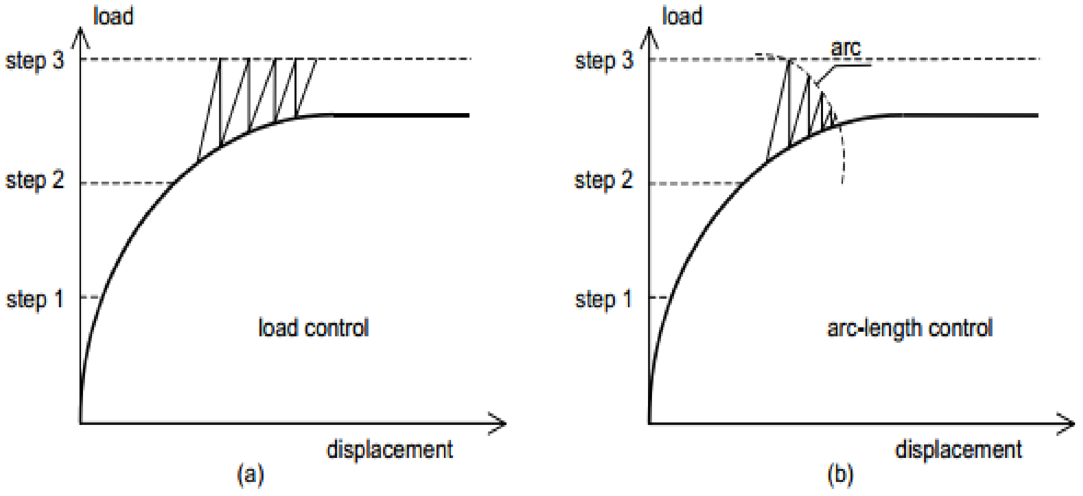


Figure 2.10 Iterative procedure for (a) normal load control (b) Arc-length control

2.3.3 Validation of PLAXIS model for the analysis

The PLAXIS model is validated using a physical model test [16] implemented to determine the failure mechanism and uplift capacity of shallow foundations.

2.4 Soil parameters for the defined soil types for tower foundations

Soil parameters for selected soil types from S2, S3, S4 and S5 soil categories are obtained from the literature. The selected soil types are given in Table 2.1.

Table 2.1 Selected soil type from soil categories used to model the transmission tower foundations

Soil Category	Selected soil type
S2	Dense gravel or sand
S3	Medium dense gravel with sand
S4	Loose gravel and sand
S5	Loose sand

Bowles [17] has proposed some reference ranges for friction angle and unit weight of cohesionless soils according to the relative density and coarseness of soils. Murthy [18] also gave ranges for friction angle of sandy soils referring particle shape and sandy gravel. Das [19] proposed some values for elastic modulus for sandy soils. Bowles

[17] also gave some values for the elastic modulus and Poisson's ratio for various type of soils. Accordingly, the selected soil parameters are given in Table 2.2.

Table 2.2 Soil parameters for selected soil types for the use of PLAXIS model

Selected Soil Type	**Friction angle**	**Cohesion (kPa)**	**Poisson's Ratio**	**Elasticity (kN/ m^2)**	**Density (kN/ m^3)**
Dense gravel or sand	38	5	0.28	35000	21.0
Medium dense gravel with sand	33	2	0.31	22500	19.5
Loose gravel and sand	29	1	0.33	12000	17.0
Loose sand	27	1	0.35	10000	16.5

Chapter 3

Analysis of foundations for uplift for different soil types

3.1 PLAXIS model validation

The configuration of the physical model [16] used to determine the failure mechanism and uplift capacity of shallow foundation is shown in Figure 3.1(a). Three model tests were implemented embedding the steel plate in three different levels of 100mm, 200mm and 300mm. The ultimate capacities of the physical test for 100mm, 200mm and 300mm are 193N, 529N and 1037N respectively. These values are determined using the load-displacement curves as shown in Figure 3.1(b).

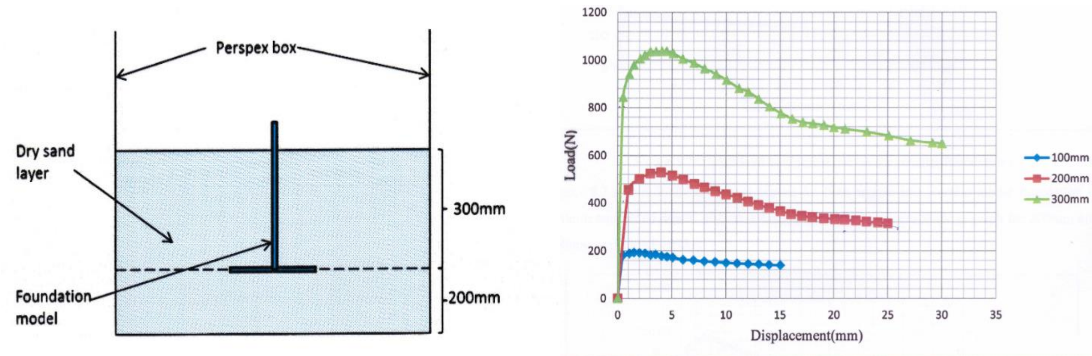


Figure 3.1 (a) Physical model used to determine the failure mechanism and uplift capacity of shallow foundation (b) load-displacement curve for the physical models

Numerical analysis for the physical model is done using the PLAXIS software. A uniform distributed load of $20kN/m^2$ was applied on the plate for every embedment depth and obtain the load-displacement curve to determine the failure load. The failure load obtained using analysis are 288N, 630N and 1107N for the 100mm, 200mm and 300mm embedment depths respectively. The results of the physical model and the numerical model are within similar range for the embedment values of 200mm and 300mm. However, the uplift capacity for the 100mm model seems to be high for the PLAXIS 3D analysis. This may be due to the variation of soil properties due to the lower depth of embedment. In conclusion, PLAXIS model has given similar uplift capacities to the physical model. The results are given in Table 3.1 comparing physical model results to the PLAXIS model results.

Table 3.1 Comparison of results by Physical and PLAXIS model

Depth of Embedment (mm)	**Uplift Capacity (N)**	
	Physical Model	**PLAXIS Model**
100	193	288
200	529	630
300	1037	1107

3.2 Correlation between uplift capacity and different soil and foundation parameters for undercut foundations

3.2.1 Development of PLAXIS model for the analysis

Mohr-Coulomb model is used to model the soil types listed in the Table 1.2. Concrete foundations are modelled using linear elastic non-porous model, because the exact shape of the foundation cannot be modelled using plates. Quadratic 6-node elements and 4^{th} order 15-node wedge elements are available for the finite analysis in this software. 15-node element is used for the analysis due to the higher nodal density and accuracy. These nodes may be degenerate once to 13-node volume elements or twice to 10-node tetrahedral elements due to non-horizontal soil stratigraphy. Global coarseness of the mesh generation is selected as very fine to take more accurate results. Shear failure is chosen as the failure criterion for the analysis of these foundations. Tolerated error of 0.01 is chosen for the reliability and accuracy of the calculation. Arc-length control is used to identify the failure load of the analysis. Calculations steps were increase to 1000 to make the PLAXIS model to be failed within the number of steps being iterated.

The uplift capacity of the foundations is determined by applying a larger load than the tentative uplift capacity and making the PLAXIS model to be failed. Then, load-displacement curve is generated for the foundation and the failure load is taken as where the curve is observed to be displayed an infinite displacement without any change in the loading step.

3.2.2 Uplift capacity variation of the undercut foundation with the width of the foundation

The variation of the uplift capacity with the variation of the foundation width is observed. A foundation with vertical column is considered for this analysis as indicated in Figure 3.2. The load is also applied vertically at the top of the column.

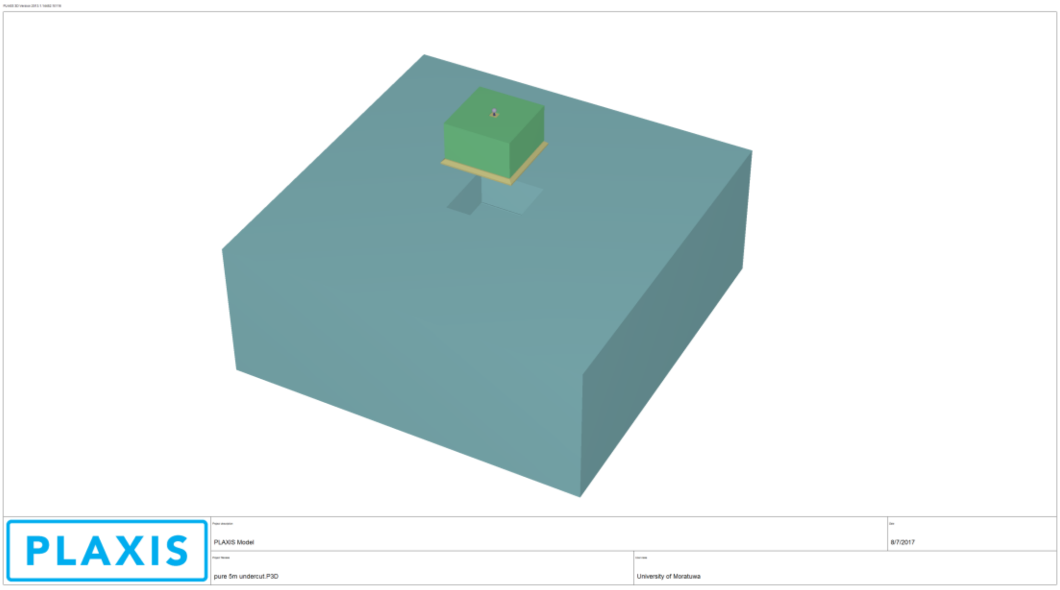


Figure 3.2 PLAXIS model developed to analyse the uplift capacity of foundation with vertical uplift load

The foundation width is varied from 3m to 6m for undercut foundations. The friction angle of the soil is considered as 38 degrees and cohesion considered is 5kPa. The other properties are remained constant for this analysis, which are 21kN/m^3, 35000kPa and 5kPa for unit density, elasticity and cohesion respectively. The analysis shows that the uplift capacity increases when the width of foundation increases. Further, it also observed that the frustum angle increases with the increase of foundation width, which results an increase of the volume of the soil inside the failure planes. The variation of uplift capacity for undercut foundations for the variation of foundation width is given in Table 3.2 and it is more elaborated in Figure 3.3. Table 3.2 further includes the calculated values of uplift capacity and its composition using the empirical methods listed in the literature review.

Table 3.2 Calculated uplift capacities for the variation of foundation width using PLAXIS 3D analysis and empirical methods

Type of Method	Method	Uplift capacity - 3m width foundation	Uplift capacity - 4m width foundation	Uplift capacity 5m width foundation	Uplift capacity 6m width foundation
FEM	PLAXIS 3D	1850	2525	3450	4680
Cone method	Dewberry	781	1360	2100	3000
	Matsuo and Tagawa	924	1513	2236	3088
	Mariupol'skii	1748	2526	3456	4532
	Mayerhof and Adams	1571	2241	3027	3929
Earth pressure method	Mueller	854	1369	2000	2746
	Mors	1180	1803	2542	3397
	Motorcolombus	915	1451	2102	2868
Semi-empirical method	Bakers and Kondner	1840	3017	4530	6380
	Turner	417	423	426	428
	Biarez and Barraud	956	1518	2208	3026

The values given by Mariupol'skii method and Mayerhof and Adams method are much closer to the values given by the PLAXIS 3D analysis. However, Bakers and Kondner, a semi empirical method gives some closer values to the lower width of foundation. But it is much higher than to the values obtained from PLAXIS 3D for wider foundations.

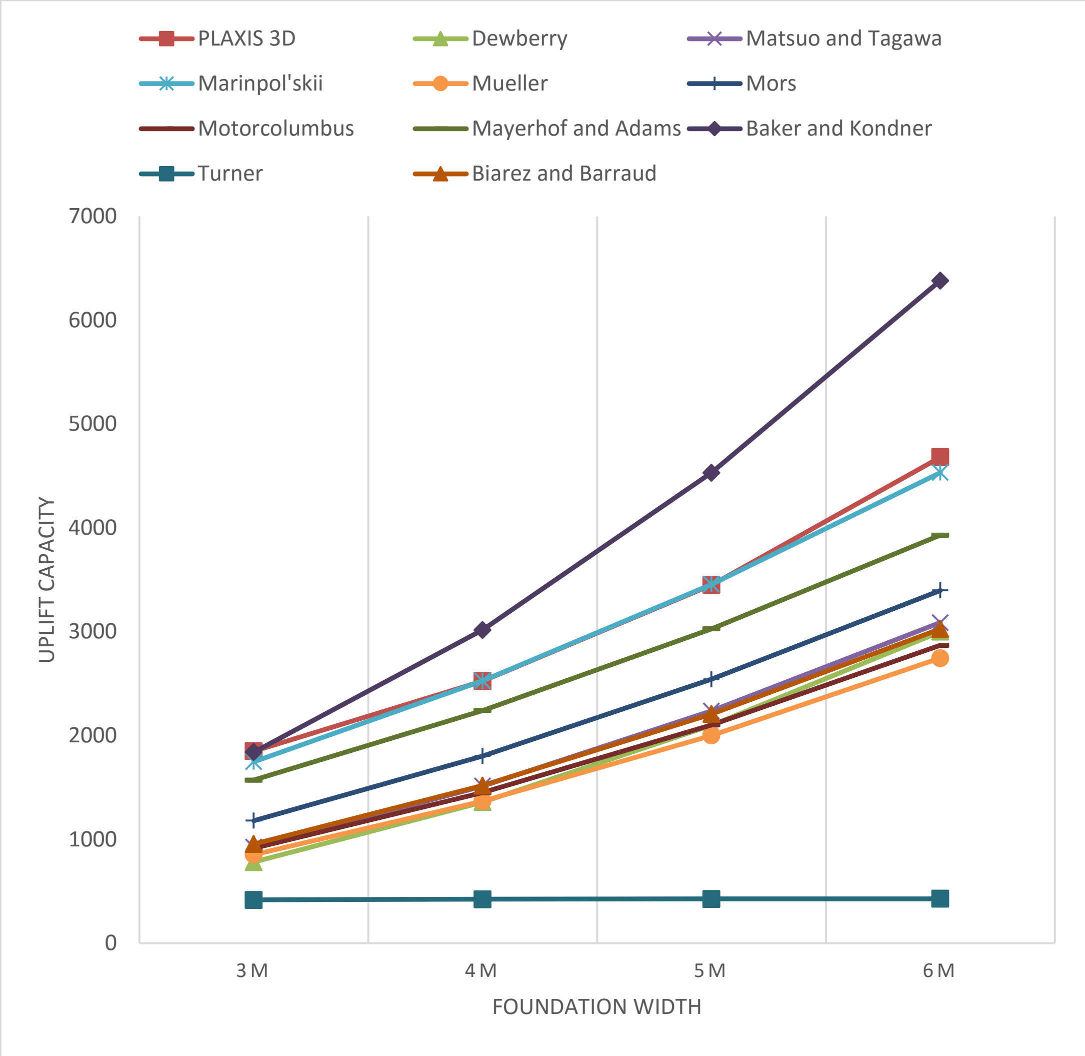


Figure 3.3 Uplift capacities given by different methods for the variation of the width of undercut foundations

3.2.3 Uplift capacity variation of the undercut foundation with the friction angle of soil

The analysis is extended to identify the variation of uplift capacity with the friction angle of the soil. The friction angle is varied from 29 to 38 degrees for the foundations with the dimension of 5m width. Other parameters are remained same as for the analysis under Section 3.2. The Turner method is not considered for this analysis as it is given very low values for the previous analysis under Section 3.2. Table 3.3 indicates the values obtained for uplift capacity for the variation of friction angle using different methods.

Table 3.3 Calculated uplift capacities of undercut foundations for the variation of soil friction angle using PLAXIS 3D and empirical methods for

Type of Method	**Method**	**Uplift capacity - ϕ = 29°**	**Uplift capacity - ϕ = 32°**	**Uplift capacity ϕ = 35°**	**Uplift capacity ϕ = 38°**
FEM	PLAXIS 3D	2975	3115	3275	3450
Cone method	Dewberry	2100	2100	2100	2100
	Matsuo and Tagawa	2197	2210	2223	2236
	Mariupol'skii	3313	3350	3391	3456
	Mayerhof and Adams	2568	2711	2863	3027
Earth pressure method	Mueller	1972	1987	1996	2000
	Mors	1982	2126	2309	2542
	Motorcolombus	1896	1954	2022	2102
Semi-empirical method	Baker and Kondner	4530	4530	4530	4530
	Biarez and Barraud	2033	2083	2145	2208

The results are graphically included in Figure 3.4. Dewberry method and Baker and Kondner method do not have the provisions to incorporate the change in friction angle to the calculation. Hence, same result is given for the variation of friction angle. Mariupol'skii method which is shown a good relationship with PLAXIS 3D analysis in Section 3.2, doesn't show a good relationship when the friction angle is varied. The gradient of the line diagram of Mariupol'skii method is not as much as high as the gradient of the line diagram of the PAXIS analysis. However, Mayerhof and Adam method gives approximately same gradient for its line diagram relative to the gradient of line diagram of PLAXIS analysis. Anyway, the results given by the Mayerhof and Adam method is approximately 13% lower than the results of PLAXIS analysis for the variation of friction angle as well as for the variation of foundation width. Other methods give lower values of uplift capacity than the PLAXIS 3D analysis results.

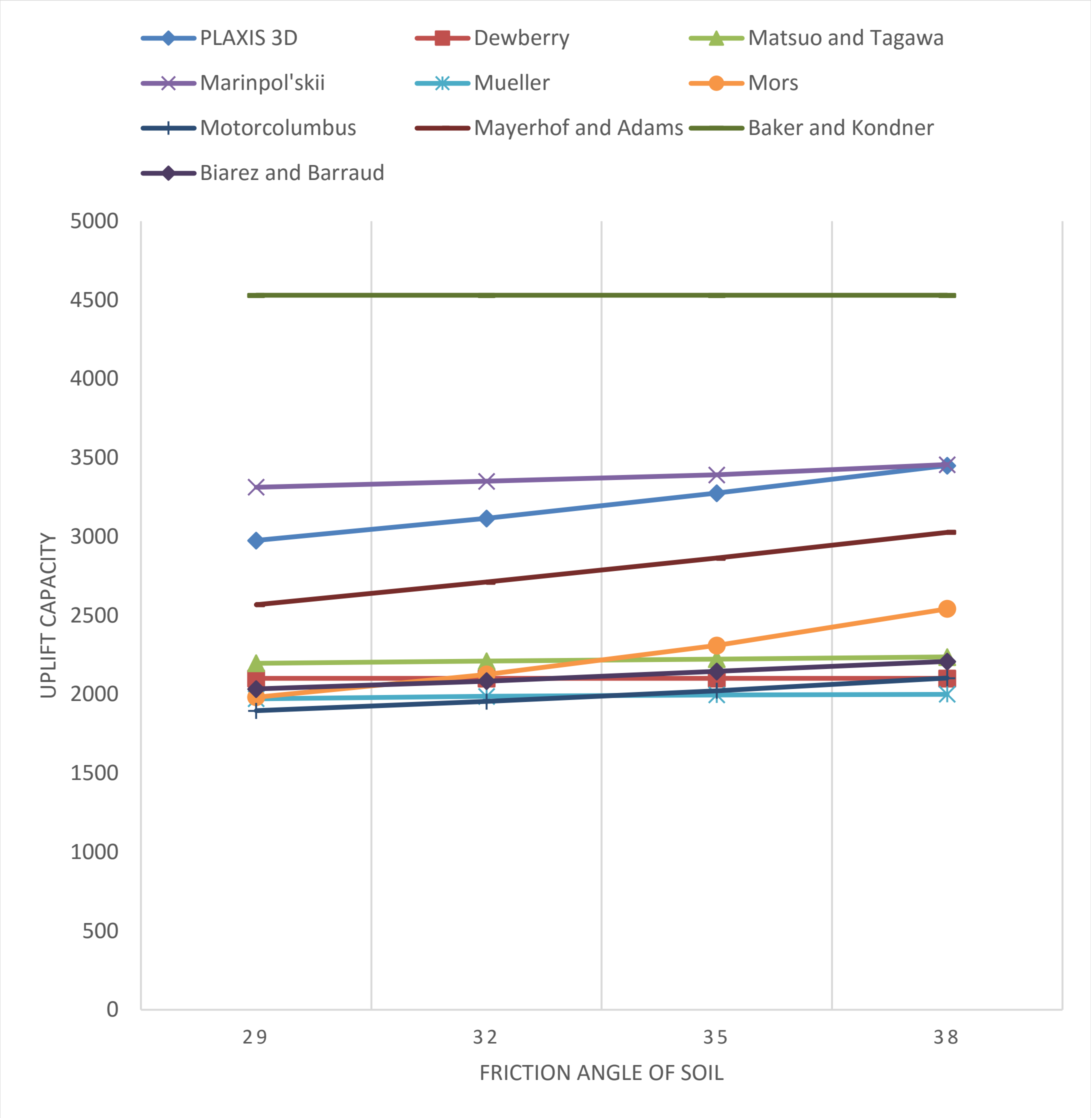


Figure 3.4 Uplift capacities given by different methods for the variation of friction angle of soil

3.2.4 Uplift capacity variation of the undercut foundation with the unit weight of soil

Unit weight of the soil is a significant factor of the uplift capacity of the foundation as it is directly related to the weight of the soil above the foundation. Hence, the analysis is done to identify the variation of the uplift capacity according to the variation of the unit weight of the soil. The friction angle, cohesion, foundation width and elasticity is remained as 38°, 5kPa, 5m and 35000kPa respectively. The results are given in Table 3.4.

Table 3.4 Calculated uplift capacities for the variation of unit weight of soil using PLAXIS 3D and empirical methods for undercut foundations

Type of Method	**Method**	**Uplift capacity - γ = 16.5kN/m^3**	**Uplift capacity - γ = 18kN/m^3**	**Uplift capacity γ = 19.5kN/m^3**	**Uplift capacity γ = 21kN/m^3**
FEM	PLAXIS 3D	2800	3025	3200	3450
Cone method	Dewberry	2100	2100	2100	2100
	Matsuo and Tagawa	1866	1989	2112	2236
	Mariupol'skii	2828	3037	3246	3456
	Mayerhof and Adams	2689	2801	2914	3027
Earth pressure method	Mueller	1882	1921	1960	2000
	Mors	2308	2386	2464	2542
	Motorcolombus	2102	2102	2102	2102
Semi-empirical method	Baker and Kondner	3559	3883	4206	4530
	Biarez and Barraud	1812	1944	2076	2208

Dewberry method and Motorcolombus method do not indicate any variation to the variation of the unit weight. Mariupol'skii method does give similar values to the PLAXIS 3D for this analysis. Incremental variation of uplift capacity to the unit weight of soil of Mayerhof and Adam method, is different from the PLAXIS 3D analysis whereas in previous analysis it is same as the PLAXIS 3D analysis. However, Baker and Kondner method gives higher values than the PLAXIS 3D analysis and other methods gives lower values to the analysis. The uplift capacities according to the variation of unit weight of soil given by various methods is elaborated in Figure 3.5.

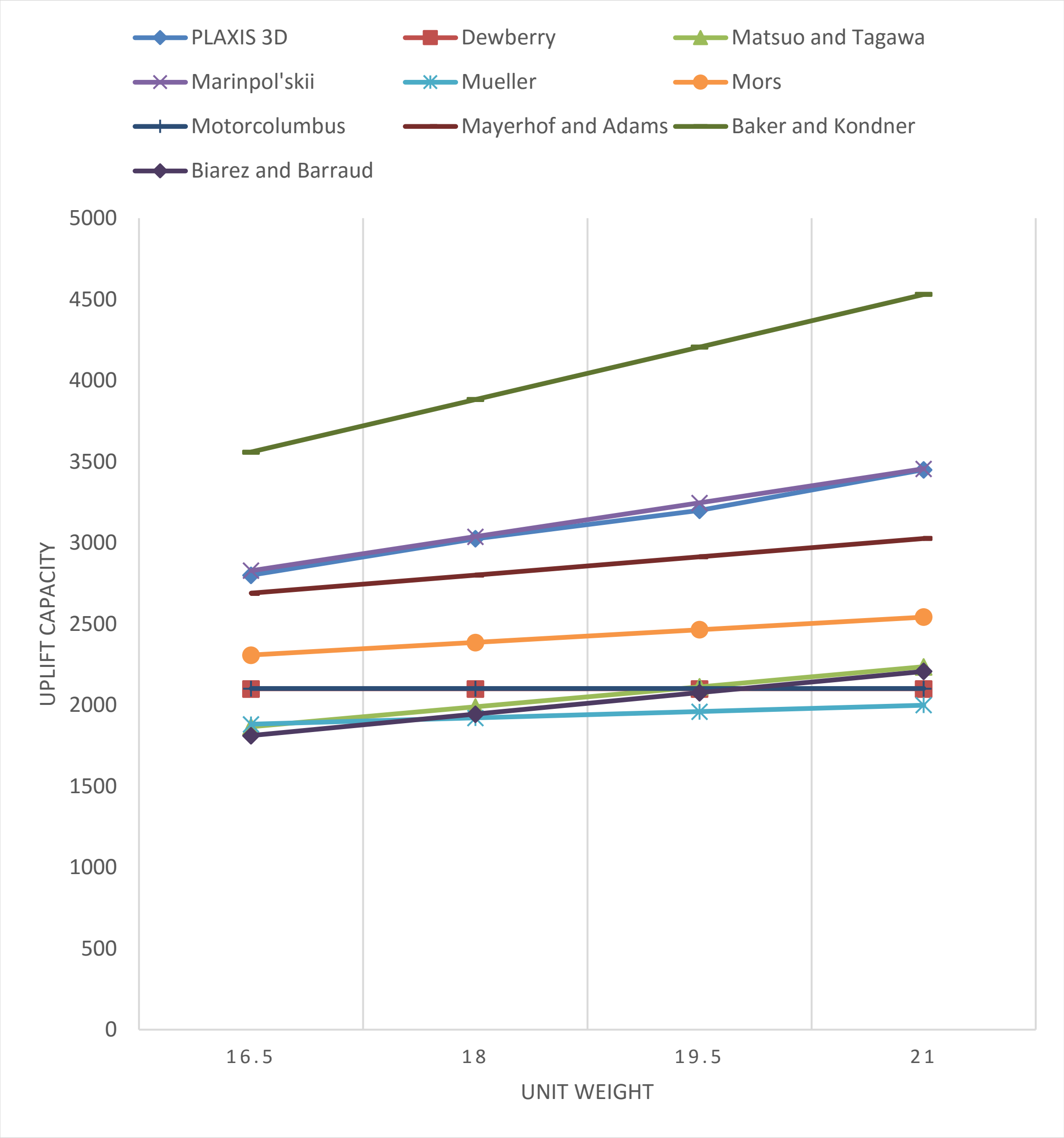


Figure 3.5 Uplift capacities given by different method for the variation of unit weight of soil

3.2.5 Uplift capacity variation of the undercut foundation with the cohesion of soil

The uplift capacity variation according to the cohesion of the soil is considered in this analysis. however, Dewberry method, Baker and Kondner method and cone methods are not considered in this analysis as those methods hasn't incorporate the cohesion of soil for the calculation of uplift capacity of soil. The results are listed in Table 3.5.

Table 3.5 Calculated uplift capacities for the variation of cohesion using PLAXIS 3D and empirical methods for undercut foundations

Type of Method	**Method**	**Uplift capacity - c = 1kPa**	**Uplift capacity - c = 3kPa**	**Uplift capacity c = 5kPa**	**Uplift capacity c = 7kPa**
FEM	PLAXIS 3D	3185	3325	3450	3555
Cone method	Matsuo and Tagawa	2008	2122	2236	2350
	Mariupol'skii	3214	3335	3456	3576
Semi-empirical method	Biarez and Barraud	2098	2153	2208	2262

According to the results obtained from PLAXIS 3D analysis and empirical method, cohesion of the soil also has an impact on the uplift capacity of the soil as it is related to the shear resistance at the failure planes. Although, it has not been considered in the earth pressure methods, Mariupol'skii method gives similar values to the uplift capacities obtained from the PLAXIS 3D analysis. However, Matsuo and Tagawa method and Biarez and Barraud method gives lower values than the analysed values. The values obtained from different methods for the analysis of uplift capacity with variation of cohesion is graphically given in Figure 3.6.

3.2.6 Uplift capacity variation of the undercut foundation with the elastic modulus of soil

The analysis also extended to identify the correlation between uplift capacity and the elasticity of the soil. Analysis is implemented on m width foundation with soil properties of 38°, 21kN/m3 and 5kPa for the friction angle, unit weight and cohesion of the soil respectively. The elasticity of soil is varied from 25000kPa to 40000kPa. However, this has not given any deviation in uplift capacity. It also observed that, any of the empirical methods included in the literature review also have not incorporated elasticity of soil in calculating the uplift capacity of shallow foundations as well.

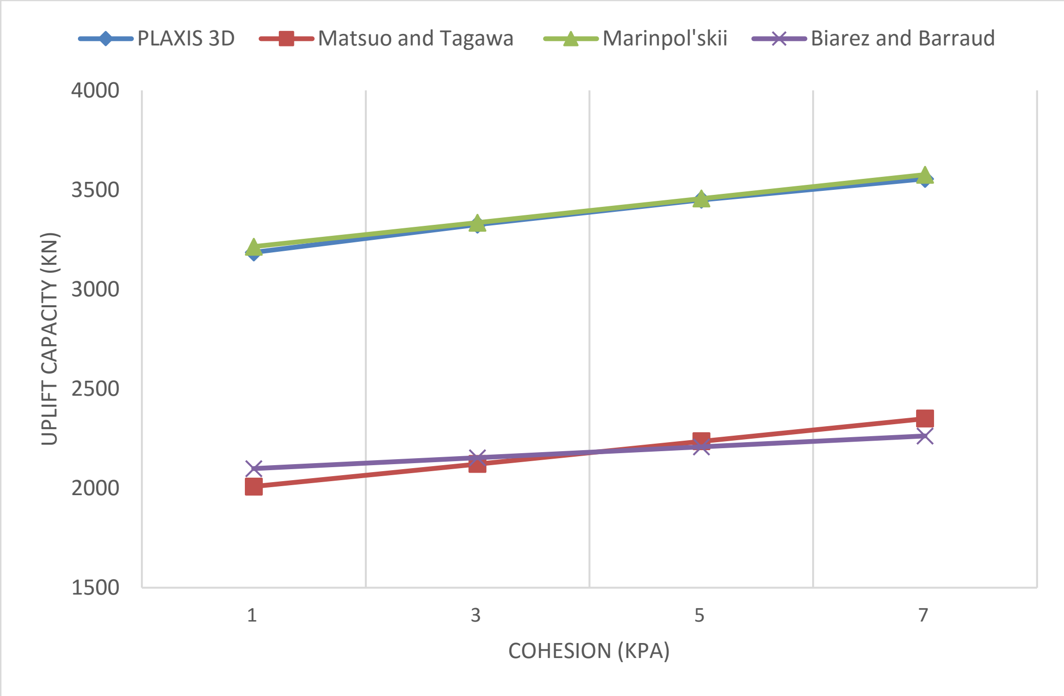


Figure 3.6 Uplift capacities given by different method for the variation of cohesion of soil

3.2.7 Uplift capacity variation of the undercut foundation with the stub direction and the load application

The direction of the application of uplift force is not vertical for transmission towers. Therefore, PLAXIS 3D analysis is implemented to observe the variation of the uplift capacity with an incline uplift forces. This direction is varied from 0 to 20° for 3m and 5m foundations. The soil parameters are 38°, 5kPa and 21kN/m^3 for friction angle, cohesion and unit weight respectively. However, the results are not compared with the empirical methods, as those methods are not developed to calculate the uplift capacity according to the inclination of uplift force. The results are tabulated in Table 3.6.

Table 3.6 Calculated uplift capacities for the variation of direction of uplift force applied, using PLAXIS 3D for 3m and 5m undercut foundations

Foundation width (m)	Uplift capacity - Vertical angle = 0	Uplift capacity - Vertical angle = 5°	Uplift capacity - Vertical angle =10°	Uplift capacity Vertical angle = 15°	Uplift capacity Vertical angle = 20°

3	1850	1860	1896	1932	1998
5	3450	3460	3490	3525	3600

According to the results, the uplift capacity doesn't change much for the inclined load within 5°. However, this becomes more significant as the inclination of applied load is increased. The inclination of all transmission towers is less than 20°. Hence, the maximum angle considered is 20°.

3.2.8 Composition of uplift capacity for variation of soil properties and dimension for the undercut foundation

The composition of uplift capacity and frustum angle are observed for different soil properties and dimensions. The results are included in the Table 3.7. The variation of soil parameters and dimension are done according to the detail given in Section 3.2, 3.3, 3.4 and 3.6.

3.3 Correlations between uplift capacity and different soil and foundation parameters for foundations without undercut

3.3.1 Uplift capacity variation of without undercut foundations with the width of the foundation

The same procedure for the undercut foundation is followed to find the correlation between the uplift capacity and the width of foundation for the foundations without undercut. The parameters are same as for the analysis mentioned is Section 3.2. Foundation width is varied from 3m to 6m, and the results are compared with the empirical calculations as given in the Table 3.8.

Table 3.7 Composition of the analysed uplift capacities of undercut foundation using PLAXIS 3D for different parameter variations

Variable soil parameter	Frustum angle (degrees)	Weight of the foundation	Weight of the soil inside the	Shear forces along the	Total uplift capacity

			(kN)	failure plane (kN)	failure plane (kN)	(kN)
Width (m)	3	11	90 (5%)	704 (38%)	1056 (57%)	1850
	4	12	149 (6%)	1163 (46%)	1212 (48%)	2525
	5	14	226 (6%)	1781 (52%)	1444 (42%)	3450
	6	15	320 (7%)	2476 (53%)	1884 (40%)	4680
Friction angle - degrees	29	10	226 (8%)	1614 (54%)	1135 (38%)	2975
	32	11	226 (7%)	1654 (53%)	1235 (40%)	3115
	35	12	226 (7%)	1695 (52%)	1354 (41%)	3275
	38	14	226 (6%)	1781 (52%)	1443 (42%)	3450
Unit weight (kN/m^3)	16.5	14	226 (8%)	1402 (50%)	1172 (42%)	2800
	18.0	14	226 (7%)	1560 (52%)	1240 (41%)	3025
	19.5	14	226 (7%)	1670 (52%)	1304 (41%)	3200
	21.0	14	226 (6%)	1781 (52%)	1444 (42%)	3450
Cohesion (kPa)	1	13	226 (7%)	1737 (55%)	1222 (38%)	3185
	3	13	226 (7%)	1737 (52%)	1362 (41%)	3325
	5	14	226 (6%)	1781 (52%)	1444 (42%)	3450
	7	14	226 (6%)	1781 (50%)	1548 (44%)	3555
Column angle - degrees	0	14	226 (6%)	1781 (52%)	1443 (42%)	3450
	5		226 (6%)	1825 (53%)	1409 (41%)	3460
	10		226 (6%)	1852 (53%)	1412 (41%)	3490
	15		226 (6%)	1854 (53%)	1445 (41%)	3525
	20		226 (6%)	1883 (52%)	1491 (42%)	3600

Table 3.8 Calculated uplift capacities for the variation of foundation width using PLAXIS 3D and empirical methods for foundations without undercut

Type of Method	Method	Uplift capacity -	Uplift capacity -	Uplift capacity	Uplift capacity

		3m width foundation	**4m width foundation**	**5m width foundation**	**6m width foundation**
FEM	PLAXIS 3D	1687	2375	3275	4224
Cone method	Dewberry	781	1360	2100	3000
	Matsuo and Tagawa	924	1513	2236	3088
	Mariupol'skii	1748	2526	3456	4532
	Mayerhof and Adams	1571	2241	3027	3929
Earth pressure method	Mueller	854	1369	2000	2746
	Mors	1180	1803	2542	3397
	Motorcolombus	915	1451	2102	2868
Semi-empirical method	Bakers and Kondner	1840	3017	4530	6380
	Turner	417	423	426	428
	Biarez and Barraud	956	1518	2208	3026

The values obtained from the PLAXIS 3D analysis seems to be closer to the values given by the Mayerhof and Adams method. Figure 3.7 shows the comparison of results graphically.

The uplift capacity seems to be lower than the values given for the foundation with undercut. This may be due to the failure planes being straight for the foundations without undercut as shown in Figure 3.8.

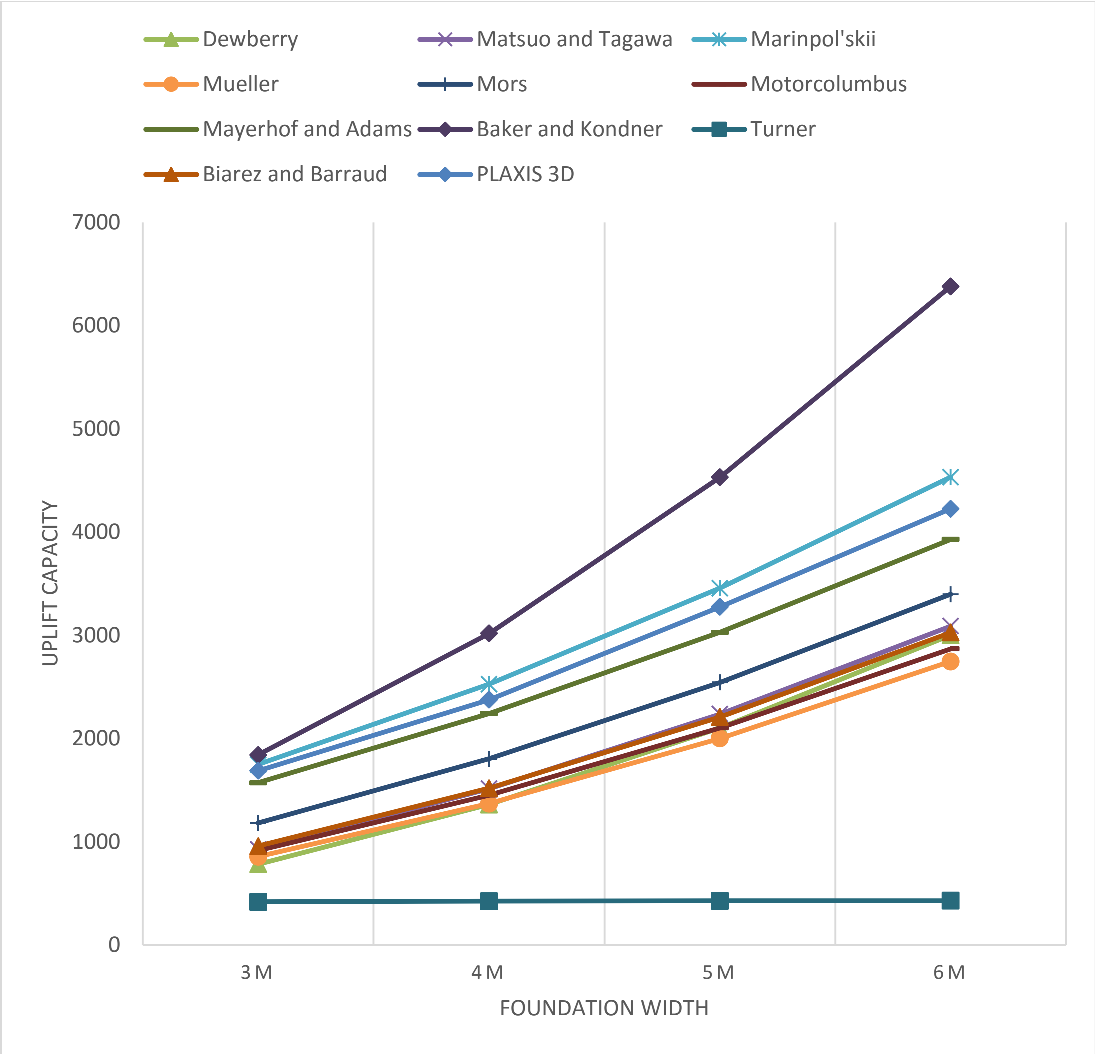
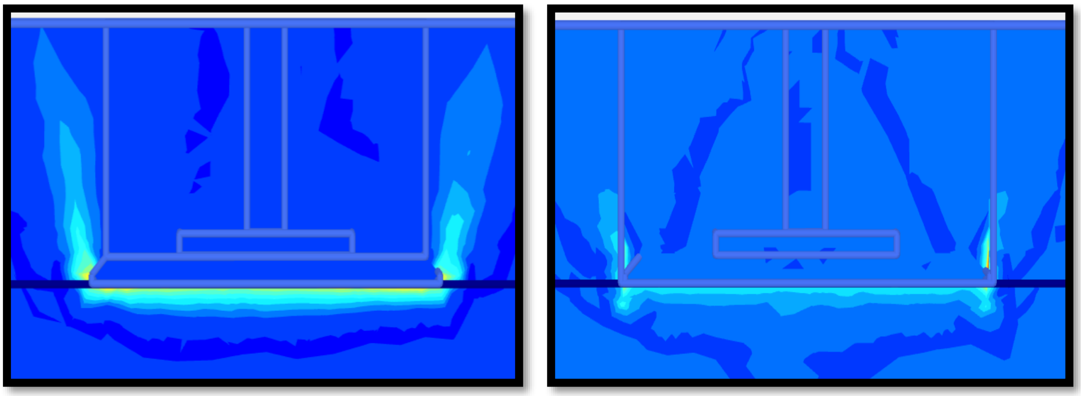


Figure 3.7 Uplift capacities given by different method for the variation of the width of foundation without undercut



(a) (b)

Figure 3.8 Failure patterns of (a) undercut foundation (b) foundation without undercut

3.3.2 Uplift capacity variation of without undercut foundations with the friction angle of soil

The Mariupol'skii method and Mayerhof and Adams methods are only concerned for this analysis, as the results of PLAXIS 3D analysis are between the values given by the said methods for all previous analysis. The results are given in Table 3.9 and Figure 3.9.

Table 3.9 Calculated uplift capacities for the variation of friction angle of soil using PLAXIS 3D and empirical methods for foundations without undercut

Type of Method	Method	Uplift capacity - ϕ = 29°	Uplift capacity - ϕ = 32°	Uplift capacity ϕ = 35°	Uplift capacity ϕ = 38°
FEM	PLAXIS 3D	2895	3000	3110	3275
Cone method	Mariupol'skii	3313	3350	3391	3456
	Mayerhof and Adams	2568	2711	2863	3027

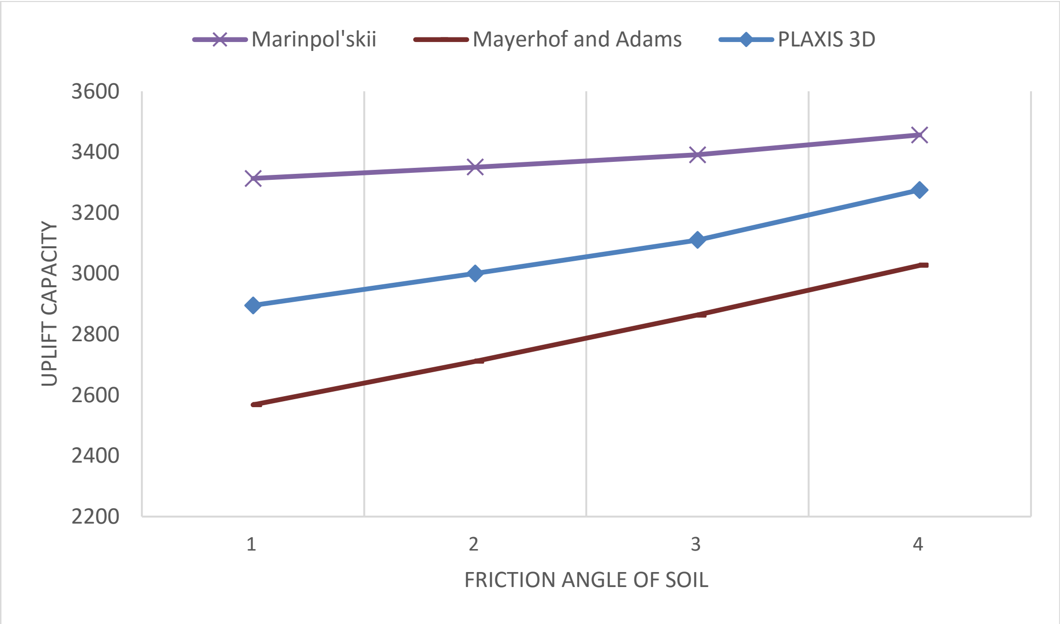


Figure 3.9 Uplift capacities given by different method for the variation of the friction angle of soil for foundation without undercut

The Mayerhof and Adams method calculates the weight of soil within failure plane, weight of foundation and frictional forces along the failure plane separately. Although, the weight of soil and foundation is same for the PLAXIS 3D analysis and Mayerhof method, the frictional forces given by the Mayerhof method seems to be lower than the PLAXIS 3D method.

3.3.3 Uplift capacity variation of without undercut foundations with the unit weight of soil

The variation of the uplift capacity of the foundations without undercut is observed. The results for this analysis also shows that the uplift capacity is lower than the uplift capacity for the undercut foundations. The considered methods are Mariupol'skii method and Mayerhof and Adams method only. The results are given in Table 3.10.

Table 3.10 Calculated uplift capacities for the variation of unit weight of soil using PLAXIS 3D and empirical methods for foundations without undercut

Type of Method	**Method**	**Uplift capacity - γ = 16.5kN/m^3**	**Uplift capacity - γ = 18kN/m^3**	**Uplift capacity γ = 19.5kN/m^3**	**Uplift capacity γ = 21kN/m^3**
FEM	PLAXIS 3D	2685	2920	3090	3275
Cone method	Mariupol'skii	3313	3350	3391	3456
	Mayerhof and Adams	2568	2711	2863	3027

The results are given in Figure 3.10 for further elaboration. The variation of the uplift capacity with the variation of unit weight is the weight of the soil within the failure plane.

Figure 3.10 Uplift capacities given by different method for the variation of the unit weight of soil for foundation without undercut

3.3.4 Uplift capacity variation of without undercut foundations with the cohesion of soil

The variation of uplift capacity of foundation without undercut with the variation of cohesion is observed. The results are given in Table 3.11 and Figure 3.11. The considered method is only the Mariupol'skii method. The cohesion of soil is not considered in calculating uplift capacity of tower foundation in Mayerhof and Adams method.

Table 3.11 Calculated uplift capacities for the variation of cohesion of soil using PLAXIS 3D and empirical methods for foundations without undercut

Type of Method	**Method**	**Uplift capacity - c = 1kPa**	**Uplift capacity - c = 3kPa**	**Uplift capacity c = 5kPa**	**Uplift capacity c = 7kPa**
FEM	PLAXIS 3D	2975	3125	3275	3385
Cone method	Mariupol'skii	3214	3335	3456	3576

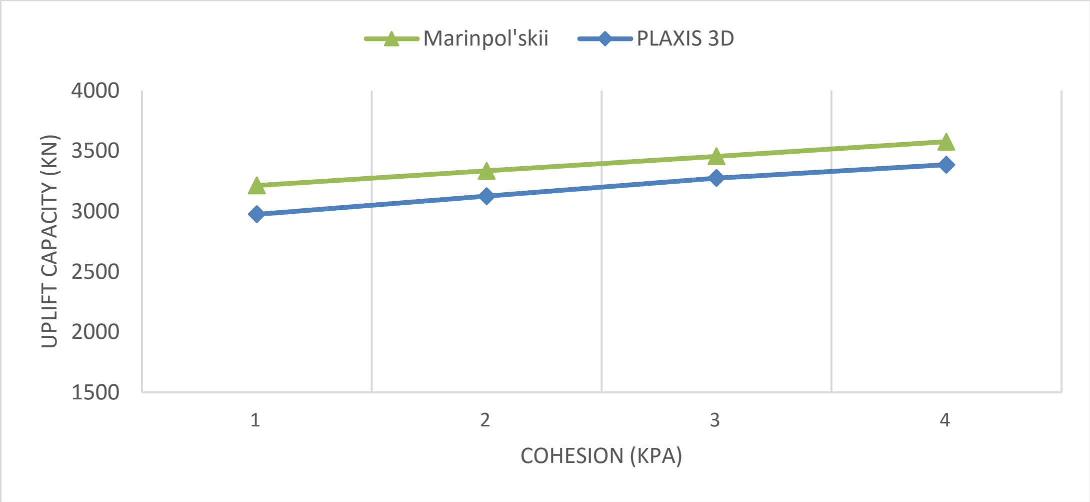


Figure 3.11 Uplift capacities given by different method for the variation of the cohesion of soil for foundation without undercut

3.3.5 Uplift capacity variation of without undercut foundations with the direction of load application and stub angle

Identifying the variation of uplift capacity with the direction of the load applied and the stub is essential for the tower foundations. Hence, the uplift capacity is observed with the direction of load applied. The results show an increase of uplift capacity with the angle of stub and load applied. However, the failure planes seem to be angled rather than vertical when the direction of the load is angled. The results are shown in Table 3.12

Table 3.12 Calculated uplift capacities for the variation of direction of uplift force applied, using PLAXIS 3D for 5m foundations without undercut

Foundation width (m)	Uplift capacity - Vertical angle = 0	Uplift capacity - Vertical angle = 5°	Uplift capacity - Vertical angle =10°	Uplift capacity Vertical angle = 15°	Uplift capacity Vertical angle = 20°
5	3275	3295	3360	3440	3520

3.3.6 Composition of uplift capacity for variation of soil properties and dimension for foundations without undercut

Analysis is summarized including the composition of uplift capacity in Table 3.13.

Table 3.13 Composition of the analysed uplift capacities for foundations without undercut for different conditions using PLAXIS 3D

Variable soil parameter		**Weight of the foundation (kN)**	**Weight of the soil inside the failure plane (kN)**	**Shear forces along the failure plane (kN)**	**Total uplift capacity (kN)**
Width (m)	3	90 (5%)	467 (28%)	1130 (67%)	1687
	4	149 (6%)	824 (35%)	1402 (59%)	2375
	5	226 (7%)	1279 (39%)	1770 (54%)	3275
	6	320 (8%)	1832 (43%)	2072 (49%)	4224
Friction angle - degrees	29	226 (8%)	1279 (44%)	1390 (48%)	2895
	32	226 (7%)	1279 (43%)	1495 (50%)	3000
	35	226 (7%)	1279 (41%)	1605 (52%)	3110
	38	226 (6%)	1279 (39%)	1770 (54%)	3275
Unit weight (kN/m^3)	16.5	226 (8%)	1010 (38%)	1449 (54%)	2685
	18.0	226 (7%)	1144 (39%)	1550 (53%)	2920
	19.5	226 (7%)	1212 (39%)	1652 (53%)	3090
	21.0	226 (7%)	1279 (39%)	1770 (54%)	3275
Cohesion (kPa)	1	226 (8%)	1279 (43%)	1470 (49%)	2975
	3	226 (7%)	1279 (41%)	1620 (52%)	3125
	5	226 (7%)	1279 (39%)	1770 (54%)	3275
	7	226 (6%)	1279 (38%)	1880 (56%)	3385
Column angle - degrees	0	226 (7%)	1279 (39%)	1770 (54%)	3275
	5	226 (7%)	1279 (39%)	1790 (54%)	3295
	10	226 (7%)	1279 (38%)	1855 (55%)	3360
	15	226 (7%)	1279 (37%)	1935 (56%)	3440
	20	226 (6%)	1279 (37%)	2015 (57%)	3520

This PLAXIS 3D analysis shows that the frustum angle is almost zero for all foundations without undercut.

3.4 Analysis of TD1-S2 foundation using PLAXIS 3D and empirical formulas

After identifying the behaving patterns of the uplift capacity according to the soil and physical parameters of the foundation, the uplift capacities of the typical tower foundations were analysed. First it was considered the design for the TD1-S2 foundation as shown in Figure 3.12, which include undercut to enhance the uplift capacity.

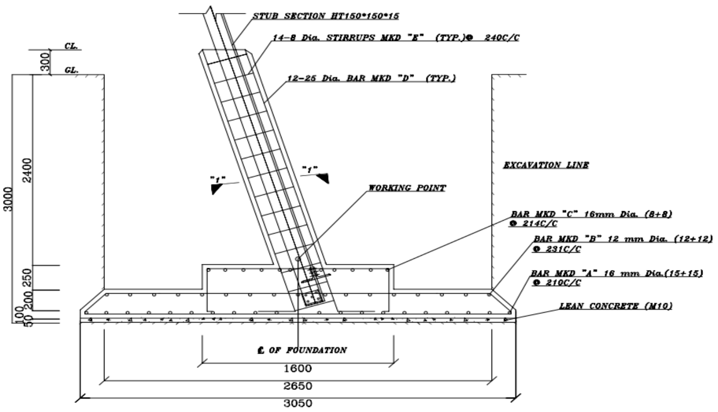


Figure 3.12 TD1-S2 type tower foundation

3.4.1 PLAXIS 3D analysis of TD1-S2 foundation

The PLAXIS model used to analyze the foundation is given in Figure 3.13.

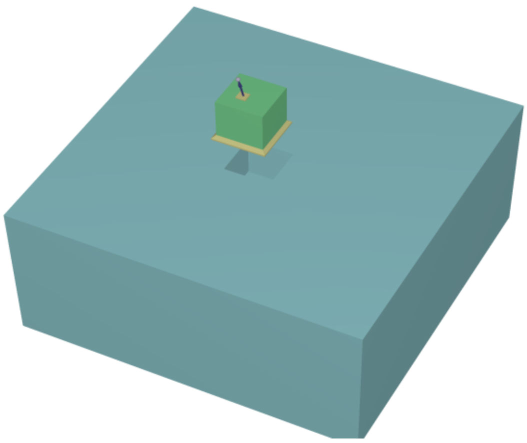


Figure 3.13 PLAXIS 3D model of TD1-S2 foundation

According to the design calculations, the calculated uplift capacity for this foundation is 1151.2 kN. The uplift capacity from the PLAXIS 3D model for the TD1-S2 tower foundation is 1930 kN. The total displacement chart from the PLAXIS analysis is shown in Figure 3.14.

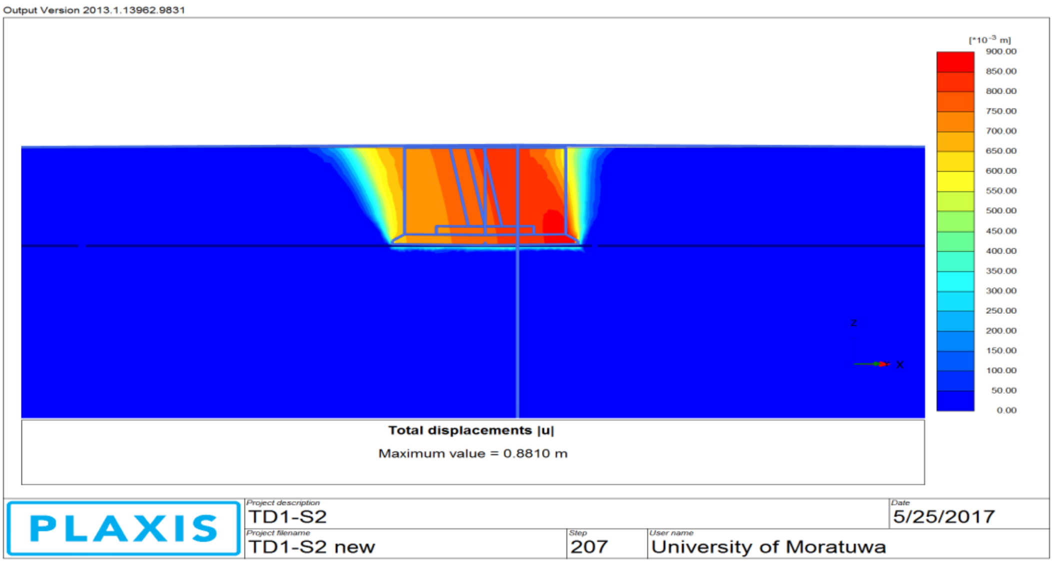


Figure 3.14 Total displacement curve of TD1-S2 tower foundation

Incremental shear strains of the PLAXIS analysis gives the failure plane of the foundation as shown in Figure 3.15.

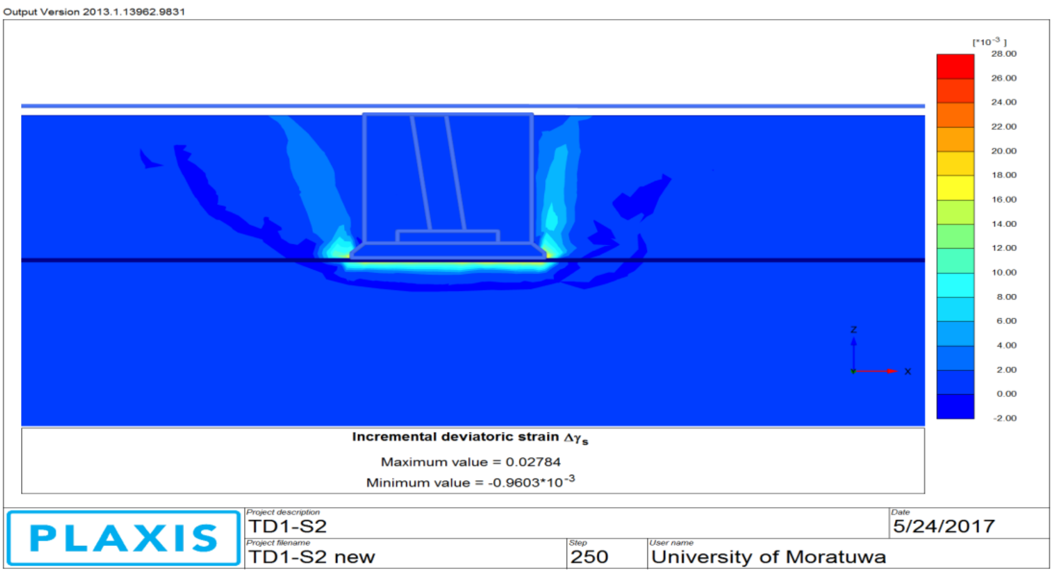


Figure 3.15 Incremental strain of TD1-S2 foundation

Frustum angle selected for the calculation of the uplift capacity of this foundation is 30 degrees. However, the failure plane is different from the assumed angles and pattern according to the PLAXIS analysis. The angle of failure plane to the vertical plane is measured and given in Figure 3.16.

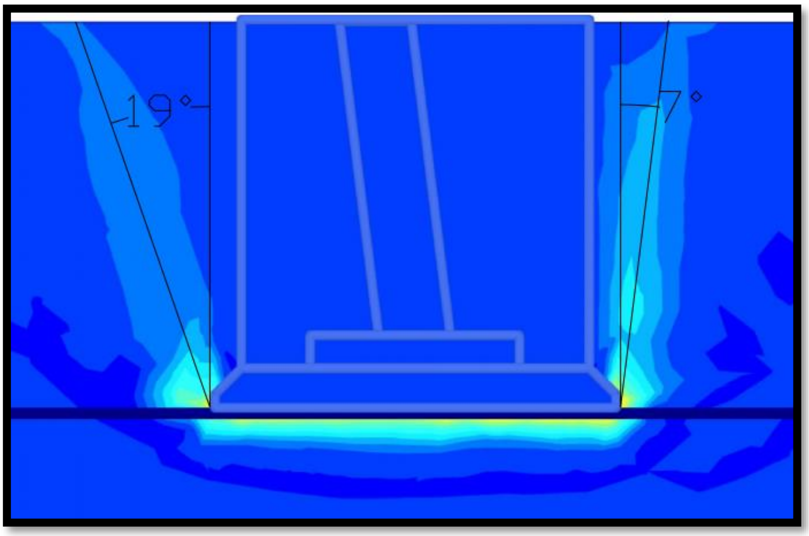


Figure 3.16 Measured angles of assumed failure plane from the PLAXIS analysis

As shown in Figure 3.16, the angle to the vertical is different for the two sides. This angle is larger at the inner edges of the load application direction. However, the failure plane seems to be match with the cone method. But, the assumed angle for the undercut foundations are different according to the results of the analysis. Further, the ultimate uplift capacity is very much higher than the designed capacity of this foundation. The shear resistance along the failure planes, which is not accounted in design may be the reason for this difference to the designed capacity. According to the obtained results from PLAXIS analysis, the shear stress along the failure plane is approximately 1049kN which is a significant portion of uplift capacity.

The soil weight within the failure planes is approximately 776kN. The weight of the foundation is 105kN. However, calculation of the shear stress at the failure planes around the foundation is much complicated process. Hence, this capacity is determined deducting the soil weight within the failure planes and the foundation weight from the given ultimate uplift capacity by the software analysis. The breakdown of the uplift capacity can be given as shown in Figure 3.17.

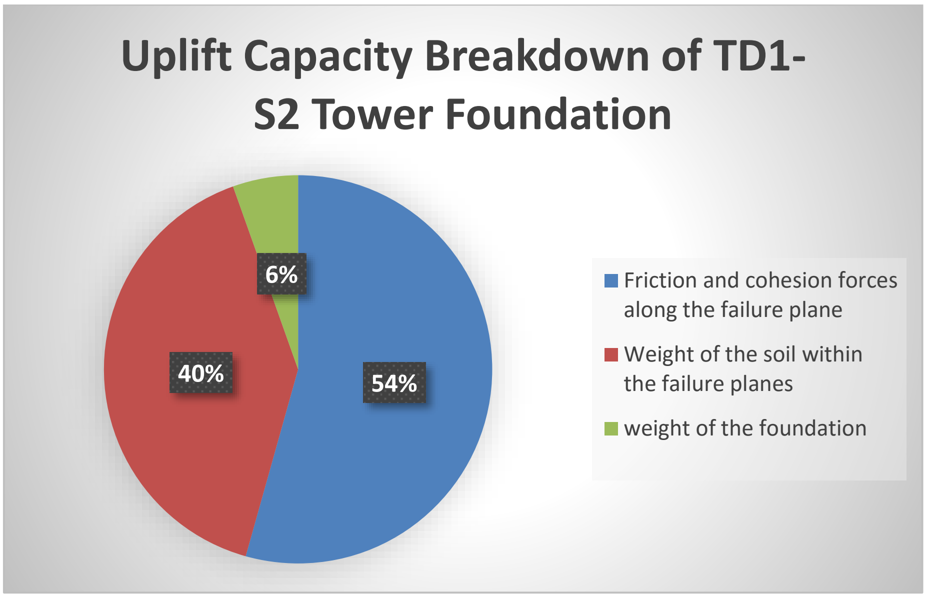


Figure 3.17 Composition of uplift capacity of TD1-S2 tower foundation

3.4.2 Uplift capacity calculation of TD1-S2 foundation using empirical formulas

According to the analysis of Section 3.3, comparable uplift capacities are given only by Mariupol'skii method and Mayerhof and Adams method. Hence, comparison of the analysed values with those two methods are given in Table 3.14. It seems that the value given to the frictional forces along the failure plane by Mayerhof and Adams method is similar to the PLAXIS 3D analysis. However, the weight of the soil within the failure plane is lesser at Mayerhof and Adams method not considered the conical shape of failure plane.

Table 3.14 Uplift capacity calculated using empirical formulas for TD1-S2 foundation

Formula	**Friction and cohesion forces along the failure plane (kN)**	**Weight of the soil along the failure plane (kN)**	**Weight of the concrete foundation (kN)**	**Total uplift capacity (kN)**
PLAXIS 3D	1049	776	105	1930
Mariupol'skii	1675		105	1780
Mayerhof and Adams	1061	438	105	1604

3.4.3 PLAXIS 3D analysis of TD1 - S3, S4 and S5 foundations and comparison of results with empirical calculations

The S3, S4 and S5 foundations do not include undercut rather than the S2 foundation. The results of the PLAXIS 3D analysis shows that uplift capacities of the foundations S3, S4 and S5 are 2090kN, 1835kN and 2720kN respectively. The failure patterns of the TD1 tower foundation type are shown in Figure 3.18.

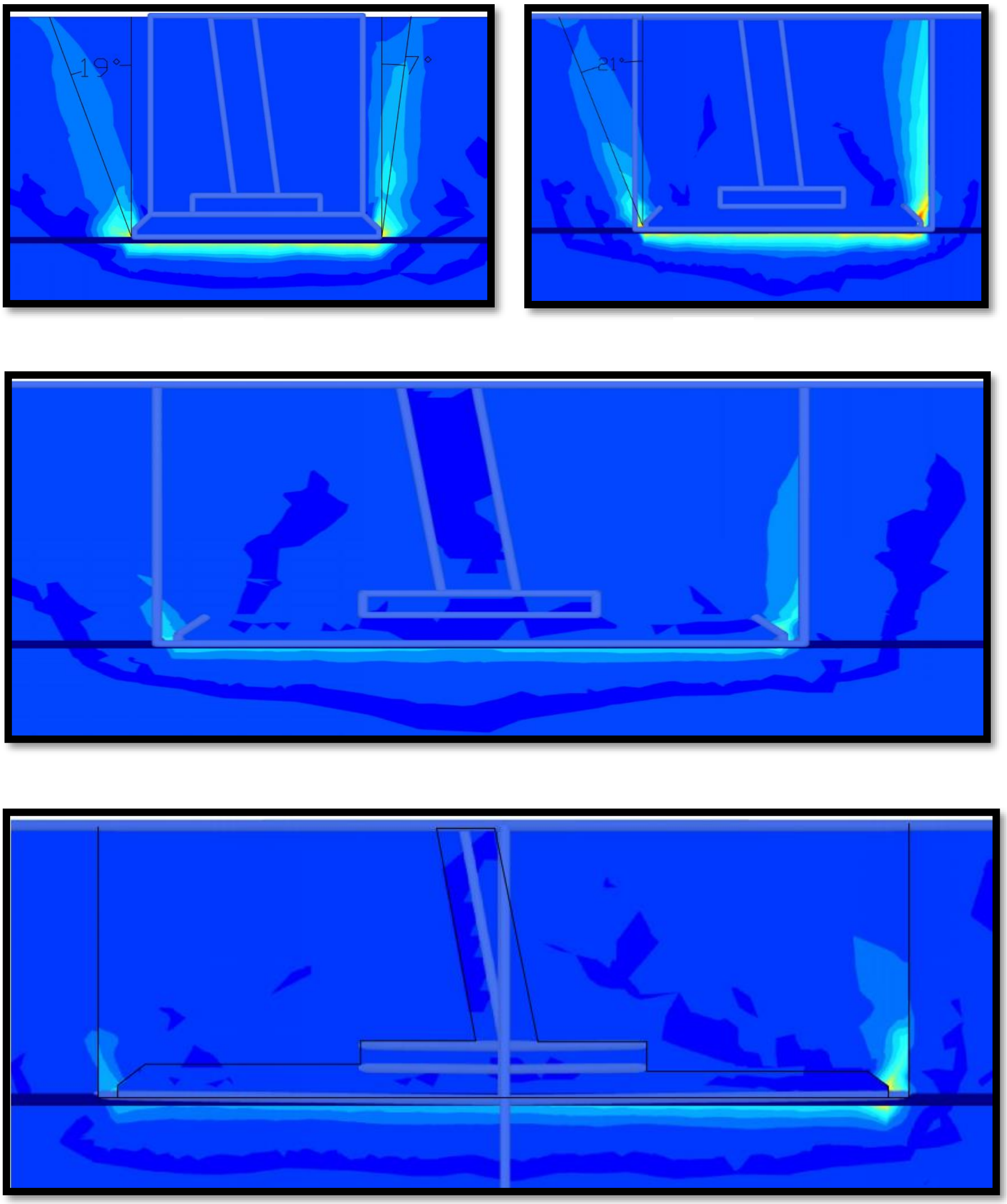


Figure 3.18 Failure patterns of TD1 foundations for the soil categories S2, S3, S4 and S5

The failure planes of the S3 foundation is similar to the failure planes of the S2 foundation even without undercut. Further, in both S2 and S3 analysis the failure plane is intercept with the surface. However, the failure occurs along the interface between existing soil and backfill according to the analysis of S4 and S5 foundations. This failure pattern is similar to the earth pressure method. However, failure plane is not intercepting with the surface. The shear forces calculated using PLAXIS analysis, soil weight within the failure plane and foundation weight are tabulated and compared in the Table 3.15 and Figure 3.19 respectively.

Table 3.15 Breakdown of uplift capacities of TD1 tower foundation types using PLAXIS 3D analysis

Foundation Type	Shear Forces (kN)	Weight of soil within failure plane (kN)	Weight of the Foundation (kN)
S2	1049	776	105
S3	965	980	145
S4	725	923	187
S5	661	1731	328

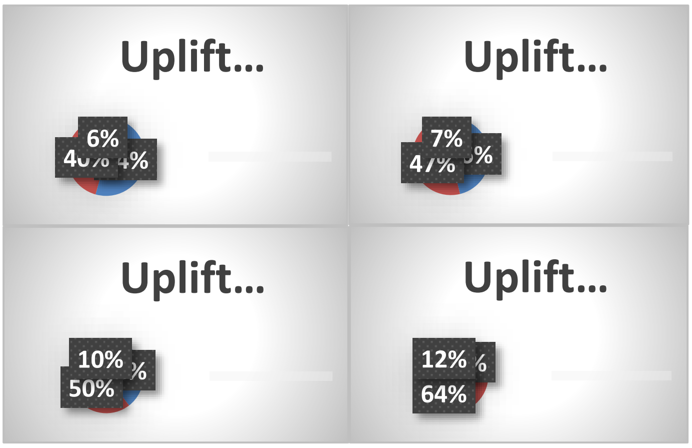


Figure 3.19 Composition of uplift capacities of TD1 tower foundation types

According to the breakdown given in Table 3.15, it can be seen that the portion of the friction and cohesion resistance at the failure of the foundation is getting decreased with the increase of the size of foundation. It also has to be considered the reduction of friction angle of the soil from the foundation type S2 to S5. The uplift capacity for the above foundations are calculated using the empirical formulas and the results are given in Table 3.16. Comparison of the results is more elaborated in Figure 3.20.

Table 3.16 Uplift capacity of foundations of TD1 tower types

Method	TD1 – S2 (kN)	TD1 – S3 (kN)	TD1 – S4 (kN)	TD1 – S5 (kN)
Designed Values	1152	1081	1076	1510
PLAXIS 3D	1930	2090	1835	2720
Mariupol'skii	1780	1982	2108	3220
Mayerhof and Adams	1604	1669	1674	2469

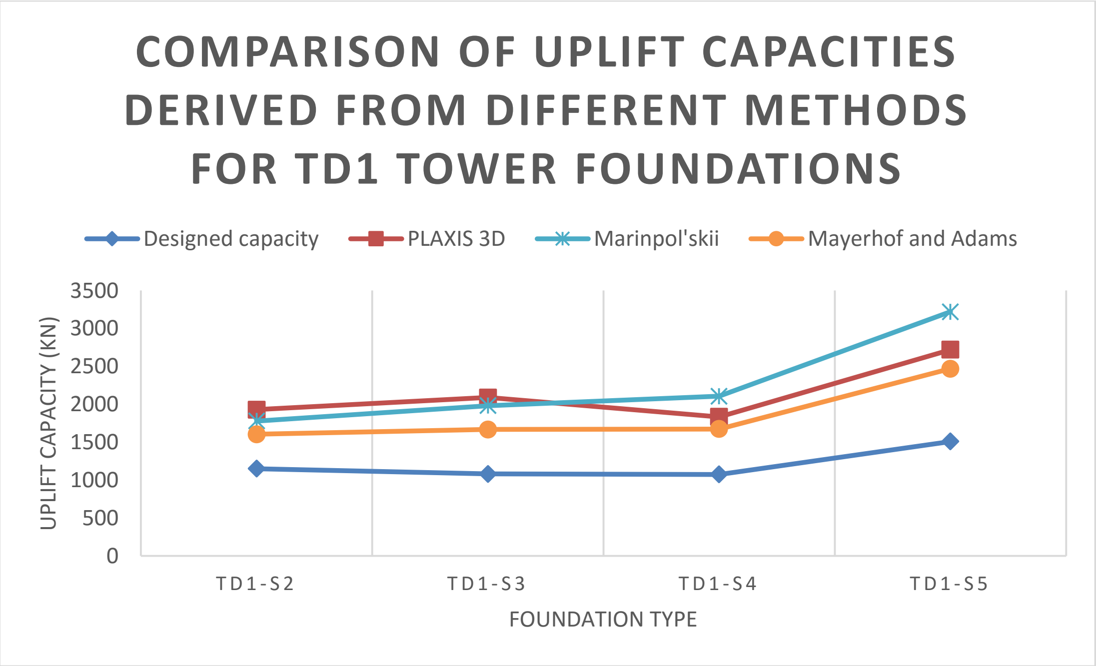


Figure 3.20 Uplift capacity of TD1 foundations derived from PLAXIS analysis and empirical formulas

3.4.4 Analysis of S2 soil type foundations

Objective of this analysis is to identify the soil behaviour with the increase of the width of the undercut foundations. TD1, TD3 and TD6 tower foundations of S2 soil type are considered for this analysis. The failure patterns for obtained from the PLAXIS analysis is given in the Figure 3.21.

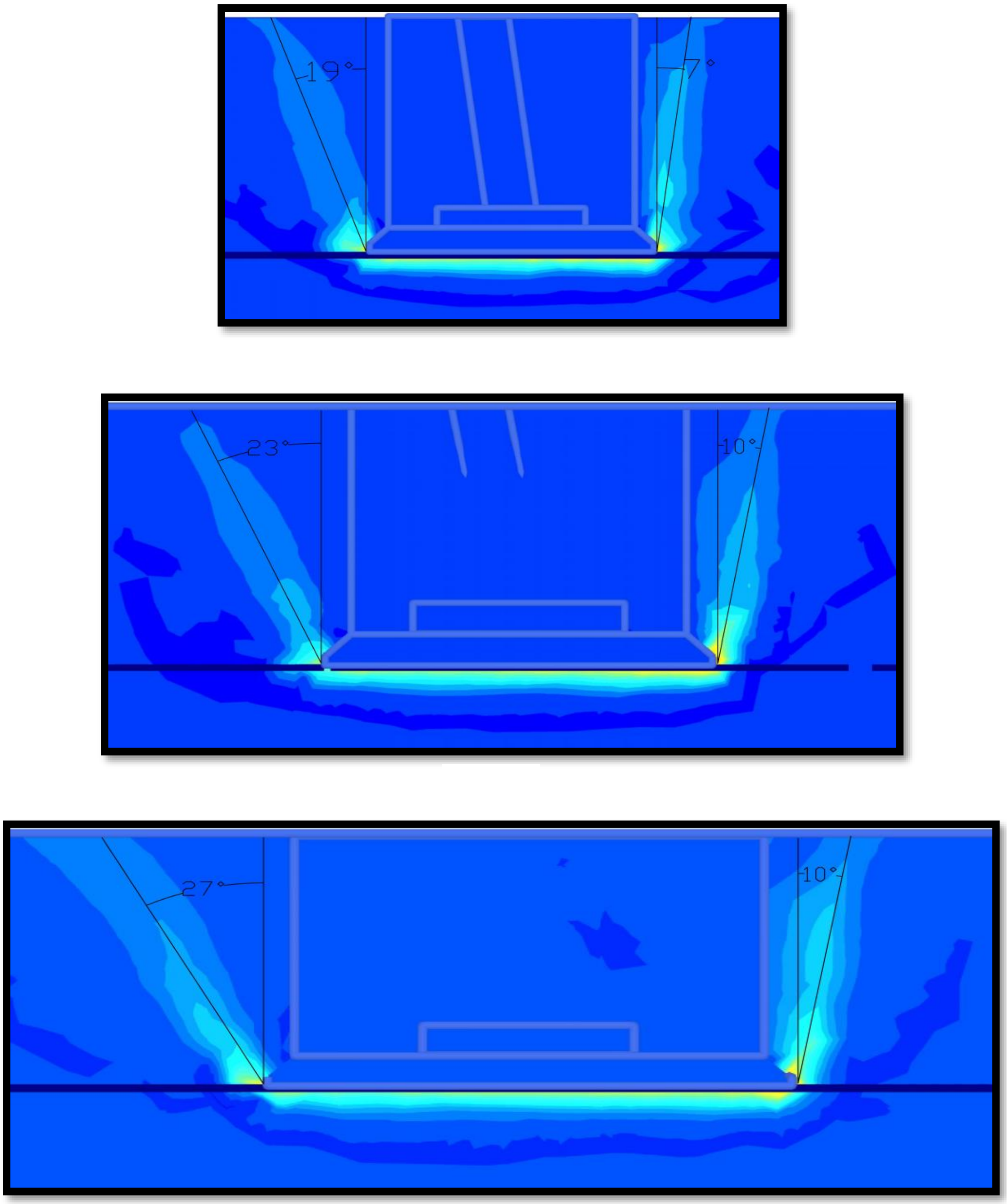


Figure 3.21 Failure patterns of S2 type foundations for TD1, TD3 and TD6 towers

The results give uplift capacities of 1930kN, 2485kN and 3590 kN for the foundations TD1-S2, TD3-S2 and TD6-S2 respectively, which are lower to the value estimates for the design of foundations. However, a conical failure plane of 30 degrees to the vertical is assumed for the design for these undercut foundations, which seems to be varied in the PLAXIS analysis. The composition of the uplift capacity of the analysed foundations are given in Figure 3.22.

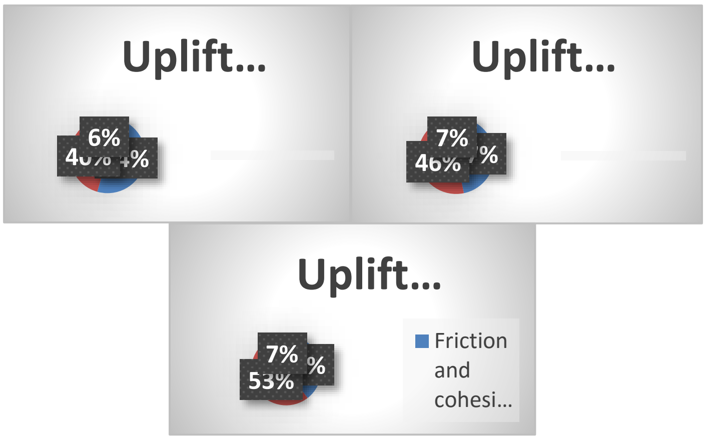


Figure 3.22 Composition of Uplift capacity of S2 type foundations

The calculated values using Mariupol'skii method and Mayerhof and Adams method are indicated in Table 3.17 and Figure 3.23.

Table 3.17 Uplift capacities of S2 foundations for all tower types

Method	**TD1 – S2 (kN)**	**TD3 – S2 (kN)**	**TD6 – S2 (kN)**
PLAXIS 3D	1930	2485	3590
Designed capacity	1151	1515	2253
Mariupol'skii	1780	2343	3405
Mayerhof and Adams	1604	2057	2953

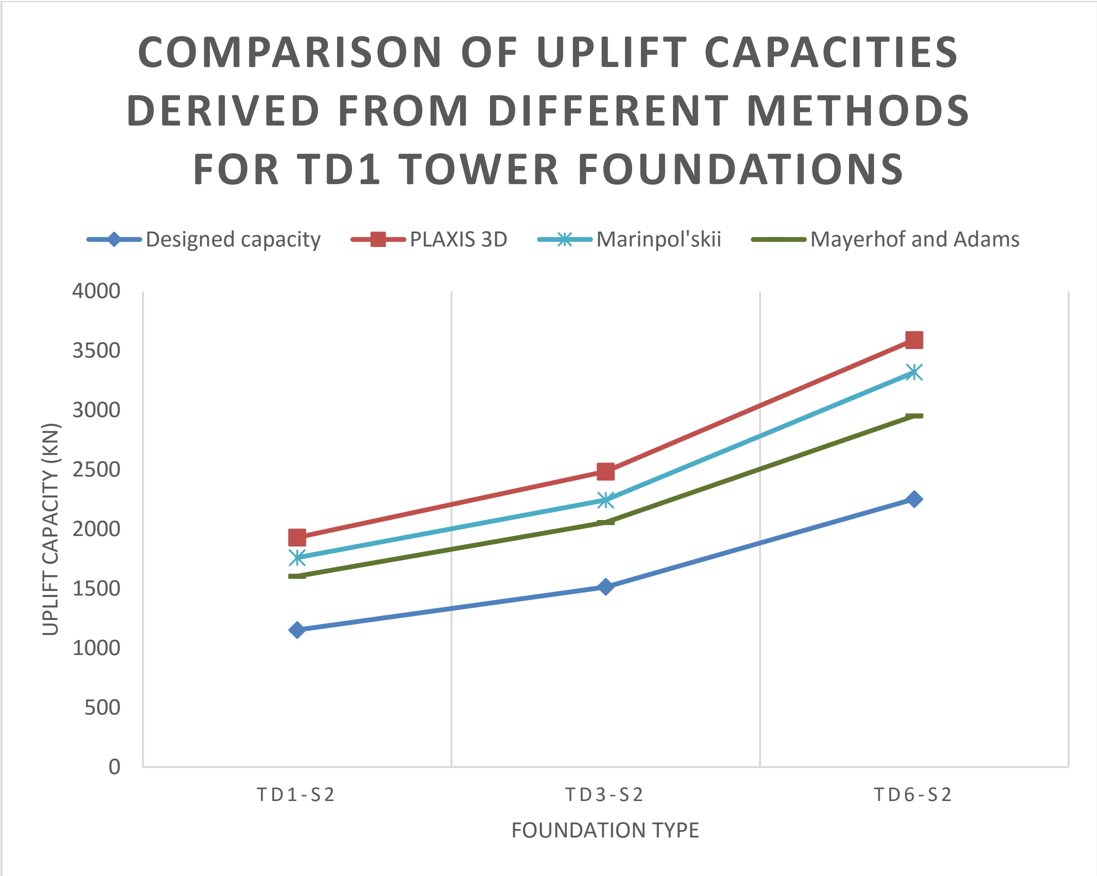


Figure 3.23 Uplift capacities of S2 foundations derived from different methods

Chapter 4

Discussion

4.1 Appropriateness of assumed failure planes in empirical methods for the purpose of calculation of uplift capacity of towers

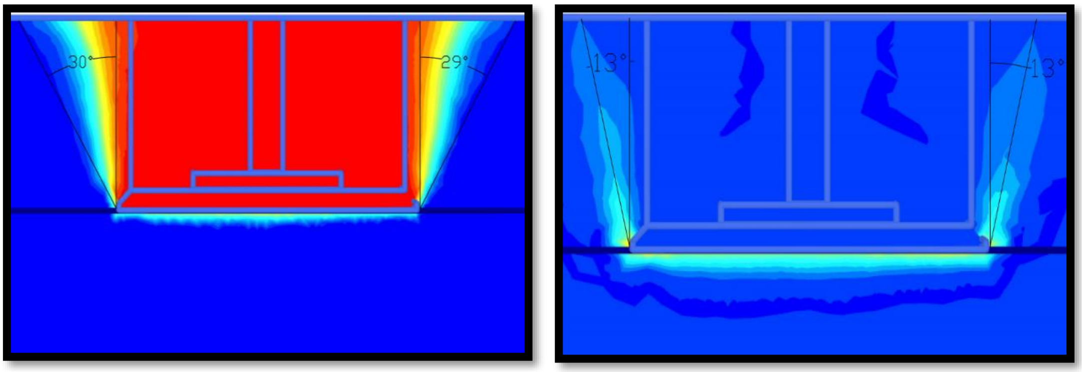
According to the literature review most of the correlations were developed assuming the failure plane is identical around the foundation. It is assumed to be inclined away around the foundation for the cone method and vertical around the foundation for the earth pressure method. Basically, the cone method is used for the calculation of the uplift capacity of the towers in recent designs. However, these empirical calculation methods are developed for the vertical loads and vertical column of foundations rather than inclined loads and inclined column of foundations.

If the foundation includes undercut and is subject to vertical load, the above assumption of the failure plane being inclined away from all sides of foundation may be justified as shown in Figure 3.10 (a) of Chapter 03. However, this assumption is differed for the foundations without undercut. The reason for this variation might be the upward movement of the soil along the separation between existing and backfilled soil. Hence, the failure planes tend to be straight as shown in Figure 3.10 (b) and assumed in Earth pressure methods.

However, these results vary with the direction of the uplift force. The results of the PLAXIS analysis shows that the failure planes of the undercut foundations tend to be asymmetrical around the foundation. Hence, the patterns of failure planes assumed in the empirical methods seems to be differed than the analyzed results. Further, the angle of the failure plane seems to be higher toward the sides where the load application is inclined. This is clearly visible in the Figure 3.22 of the Chapter 03.

According to the basic design assumptions, the frustum angle is considered as 30 degrees and 20 degrees for the undercut and normal foundation respectively. However, this assumption varies according to the analysed results. The results for the undercut foundations show that, this angle varies between 10 to 14 degrees with the foundation width and soil properties. Further, this is almost zero for the foundations without undercut. The frustum angle is differing maximum up to 27 degrees with the angle of the load application and width of foundation limited to maximum of 15 degrees and 6m respectively.

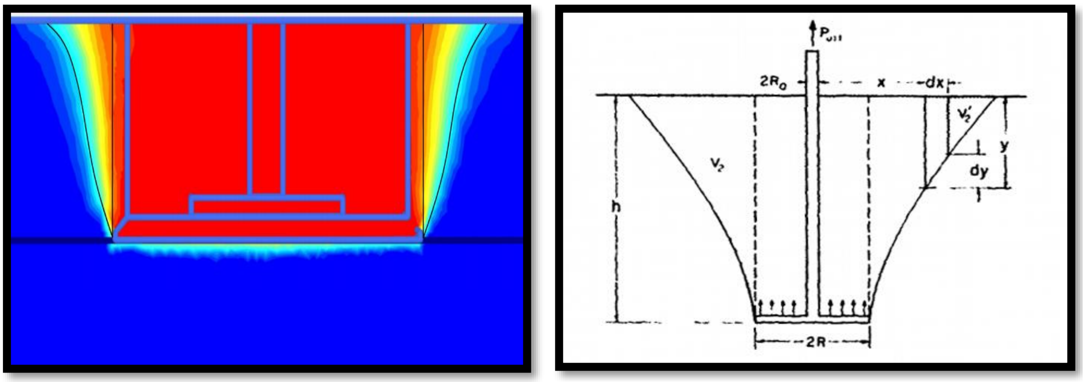
The assumption of the frustum angle for most cone methods were based on the observations made on the physical models and the full-scale tests. In these observations, it may be very difficult to identify the actual failure plane. Hence, the frustum angle may be decided according to the observations made on uplift capacity or physical displacement. This fact can be more elaborated as shown in Figure 4.1.



(a) (b)

Figure 4.1 Observations of 5m width undercut foundation (a) total displacements (b) incremental strains

If the frustum angle is decided based on the displacement as shown in Figure 4.1 (a), the angle may be assumed as 30 degrees. According to the PLAXIS 3D analysis, the failure plane occurs with an angle of 13 degrees to the vertical, as shown in Figure 4.1 (b). However, identifying the failure plane given by PLAXIS 3D analysis in a physical model seems to be very difficult. Therefore, frustum angle of 30 degrees might have assumed for most cone methods. This assumption seems to be differed in modified cone methods introduced later by Mariupol'skii. According to the Figure 2.4, the assumed failure plane is curved for the Mariupol'skii method. According to Figure 4.1 (a), it is visible a curvier displacement pattern. This is very much similar to the failure plane assumed by the Mariupol'skii as shown in Figure 4.2.



(a) (b)

Figure 4.2 (a) Displacement curve for PLAXIS 3D (b) Assumed failure plane in Mariupol'skii method

According to the Figure 4.2 (a) the failure plane can be identified as a curved line from the displacement which may match with the failure plane assumed in Mariupol'skii method as shown in Figure 4.2 (b).

However, the failure plane for the foundations without undercut may be vertical as assumed in earth pressure methods. However, local failure is observed at the top surface edges of the foundation slab. According to the analysis results, the failure plane may propagate along the separation between existing soil and backfill. This is clearly indicated in Figure 4.3 (a).

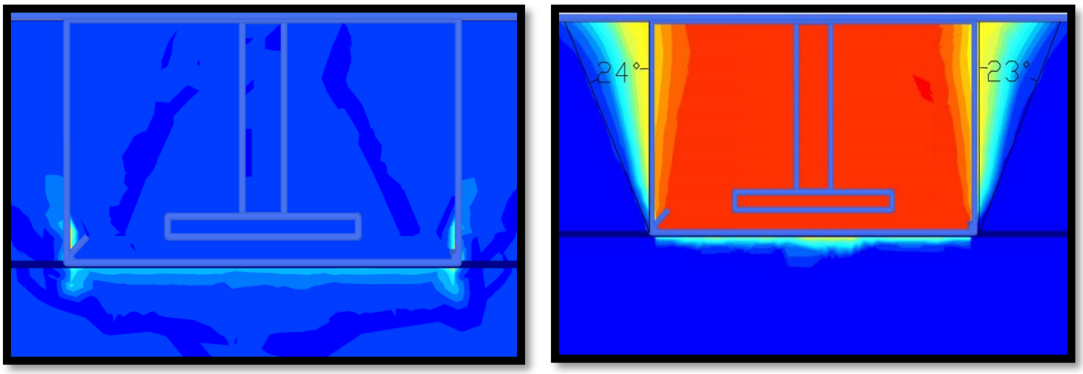


Figure 4.3 Analysis results for 5m width foundation (a) Failure plane from incremental strain curve (b) Total displacement curve

If the displacement of the soil is considered according to the Figure 4.3 (b), the curve suggests a visible displacement of soil cone which makes an angle of approximately

24 to the vertical. This is in similar range to the assumed angle in some of the empirical cone methods.

This is varied when the load application angle is varied. The failure plane which is at the load application direction seems to be angled rather than vertical as indicated in the Figure3.19. According to the said figure, the said deviation is visible for TD1 – S3 which is a foundation without undercut. However, this effect seems to get decrease with the increase of the foundation width as seen in the TD1-S4 and S5 which are larger than the TD1-S3 foundation.

4.2 Suitability of proposed empirical equations to use for the calculation of uplift capacity of tower foundations

According to the analyzed results and the empirical data, the uplift capacity of transmission tower foundation is comprised with three main components namely weight of the footing, weight of the soil within the failure planes and shear forces along the failure plane. However, the PLAXIS analyzed results are comparatively higher than the designed capacities. This is more elaborated in Table 3.15 and 3.16. According to the analysis in Chapter 3.2 and 3.3, Baker and Kondner method gives some higher values than the Analysis results of PLAXIS 3D. Hence, it is not considered as a reliable method for calculating uplift capacity of tower foundations. Further, all other methods except Mariupol'skii method and Mayerhof and Adams method give some lower range values than the PLAXIS 3D analysis results. Hence, those are not further considered for the analysis as well. However, according to the Mariupol'skii method gives closer values of uplift capacity to PLAXIS analysis in variation of foundation width, soil unit weight and cohesion for undercut foundations. However, the incremental variation of the uplift capacity with the variation of friction angle of soil is differ to the result of the PLAXIS 3D analysis. Further, Mariupol'skii method doesn't give the variation of the uplift capacity with the variation of column angle and the angle of the load application. It seems to give higher values of uplift capacity when the column and the load application is angled.

The results for the analysis of foundation without undercut is different from the results of the undercut foundations. Basically, the uplift capacity of foundation without undercut is lower than the uplift capacity of foundation without undercut for the same soil and foundation properties. The main reason for this reduction of the uplift capacity is the failure pattern. The foundation without undercut tends to be failed vertical between the virtual joint of existing soil and the backfill. Therefore, the shear capacity and the weight of the soil uplifted are lower than for the uplift capacity of the undercut foundation.

The analysis shows that, the uplift capacities given for analysis of variation of foundation width and soil friction angle, cohesion and unit weight are lies between the uplift capacities given by the Mariupol'skii method and Mayerhof and Adams method. Mariupol'skii method gives higher values and Mayerhof and Adams method gives lower values. However, when the column angle is varied the value of the uplift capacity tends to gradually get closer to the values given by the Mariupol'skii method.

According to the results of the existing tower foundation analysis in chapter 03, the uplift capacities given for the undercut foundations and foundations without undercut of lower widths by PLAXIS 3D analysis, tends to be higher than the values given by the Mariupol'skii method and Mayerhof and Adams method. But, the uplift capacities given by the PLAXIS 3D analysis for the foundation without undercut of larger widths are between the values given by the Mariupol'skii method and Mayerhof and Adams method. However, considering the variations of the soil properties and foundation dimensions which may occur in constructing the tower foundations, it might be more convenient and reliable to use Mayerhof and Adams method in calculating the uplift capacities of transmission tower foundations.

4.3 Composition of uplift capacity of a foundation

According to the literature review, weight of the foundation, weight of the soil within the failure planes and the shear forces along the failure planes are the major three components of the uplift capacity of a shallow foundation. However, the composition of these three factors are varying with the variation of foundation dimensions and soil properties.

The results elaborated in Table 3.6 shows a significant variation of the composition of the uplift capacity with the variation of foundation width for the foundations with undercut. The shear stresses along the failure plane has high percentage of the uplift capacity for foundations which has the foundation widths 3m and 4m. These foundations have depth to width ratio of 1 and 0.75 respectively. However, when the foundation gets larger, the portion of shear stress along the failure planes become lesser and the soil weight within the failure plane becomes larger.

When the soil properties of the 5m width undercut foundation, the composition of the uplift capacities are at similar ranges. However, when the cohesion and friction angle of the soil is increased, the shear forces along the failure plane are increased rather than the incremental increase of the weight of the soil within the failure planes. The weight of the soil within the failure plane may be increased due to the increase of the frustum angle by two or three degrees. But, the variation is vice versa when the unit weight of the soil is changed. The frustum angle is hardly not changed for this variation. However, the weight of the soil within the failure planes increases due to the increase of the unit weight. Further, a slight increase of the frictional forces along the failure planes is noticed. Increase of the vertical stress along the failure plane due to the increase of the unit weight may be caused to this slight increase of the frictional forces along the failure plane.

The variation of the uplift capacity with the variation of load application direction is not linear. The increase of uplift capacity is very much low up to 5-degree increase of load application direction. However, the incremental change of uplift capacity is increased after change of load application direction above 5 degrees. It seems the soil weight within the failure plane increases with the load application angle. It can be seen one of the failure plane angles more toward the load application direction as shown in Figure 4.3.

However, the above stated conclusions were made on the assumed failure plane according to the output of the PLAXIS 3D analysis. Therefore, the results may slightly vary for a small variation of the assumed failure plane. However, this may not have broad impact on the end results of the composition of the uplift capacity.

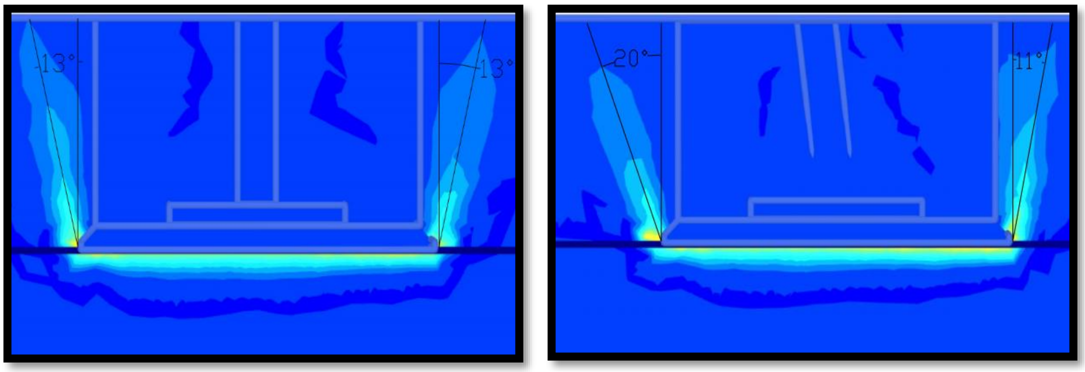


Figure 4.4 Incremental strains of 5m undercut foundation (a) vertical uplift force (b) 15 degree angle uplift force

A larger portion of the uplift capacity is given by the shear forces along the failure plane for the foundation without undercut. The failure plane remains vertical in the analysis results for almost all soil property and foundation variations. An increase of the frictional forces along failure plane is observed in the proportion calculation of the foundation without undercut than for the undercut foundations as shown in Table 3.12. The percentage of weight of the soil within the failure planes remains constant in most cases unless otherwise the unit weight of the soil is changed. The failure planes seem to remain vertical even for the change in the load application direction.

The discussed patterns are same for the designed transmission tower foundations as well. Shear force along the failure planes is dominant in uplift capacity for the foundations with depth to width ratio around one. However, the weight of the soil within the failure plane is dominant for the foundations with depth to width ratio lesser than one.

Chapter 5

Conclusion

5.1 Conclusions

Following conclusions are made from this study and implementation

1. The frustum angles assumed in empirical method are different with the PLAXIS 3D analysis results. According to the results, the frustum angle for the undercut foundations with depth to width ratio of 0.5 to 1, is varied between 10 to 15 degrees for the application of vertical uplift forces.
2. When the load application is inclined, the frustum angle around the foundation tends to be unsymmetrical. Frustum angle inside the load angle direction is higher than the angle of other sides. This angle is increasing with the increase of the foundation width of undercut foundations.
3. The frustum angle is zero for the foundations without undercut at 3m depth for vertical loading. It is observed that, a failure planes occurs at the bottom of the foundation only. It may propagate through the joint between the existing soil and backfill.
4. The failure plane is angled at the side of the uplift force is inclined as well for the foundations without undercut with a depth to width ratio around 1.
5. Mariupol'skii method gives similar values to the uplift capacities given by the PLAXIS 3D analysis for most uplift capacity determination of undercut foundations with vertical uplift forces. However, when the uplift load is inclined as in transmission tower foundation, the capacities given for undercut foundations by PLAXIS 3D analysis are slightly higher than the Mariupol'skii method. Further, it gives similar range values for foundations without undercut which have depth to width ratio of approximately 1. Hence, it may use to determine the uplift capacity of transmission tower foundations with undercut.
6. Mayerhof and Adams method gives slightly lower values than the PLAXIS 3D analysis for almost all cases considered. Hence, this method may be more conservative to use to calculate the uplift capacities of transmission tower foundations due to imperfections in construction process.

7. Uplift capacities of foundations are increased linearly with the increase of friction angle, cohesion and unit weight of soil. It is also increased linearly with the increase of the width of the foundation. However, the analysis shows that, it is not deviated with the deviation of Elasticity of soil. This fact is also evident by the empirical methods as well by not including the Elasticity of soil for all empirical equations considered.
8. Despite the shear stress is not considered in current design procedure for transmission tower foundations, the analysis shows that, the shear stress developed along failure planes is a significant factor of Uplift capacity of tower foundations. It occupies 40-60% of the uplift capacity depending on the foundation width. The percentage of composition occupy by the shear stress along the failure plane decrease with the increase of the foundation width.

5.2 Suggestion to be implemented

Extending of this research is crucial to further explore.

1. The variation of uplift capacities for both undercut and without undercut foundations in cohesive soils.
2. Development of an accurate correlation to determine the shear forces along the failure surface and weight of the soil uplifted with the variation of soil properties, foundation dimensions and angle od load application.
3. Identification of the behavior of all four foundations when the uplift and compressive forces are applied on relevant foundations according to the tower analysis.

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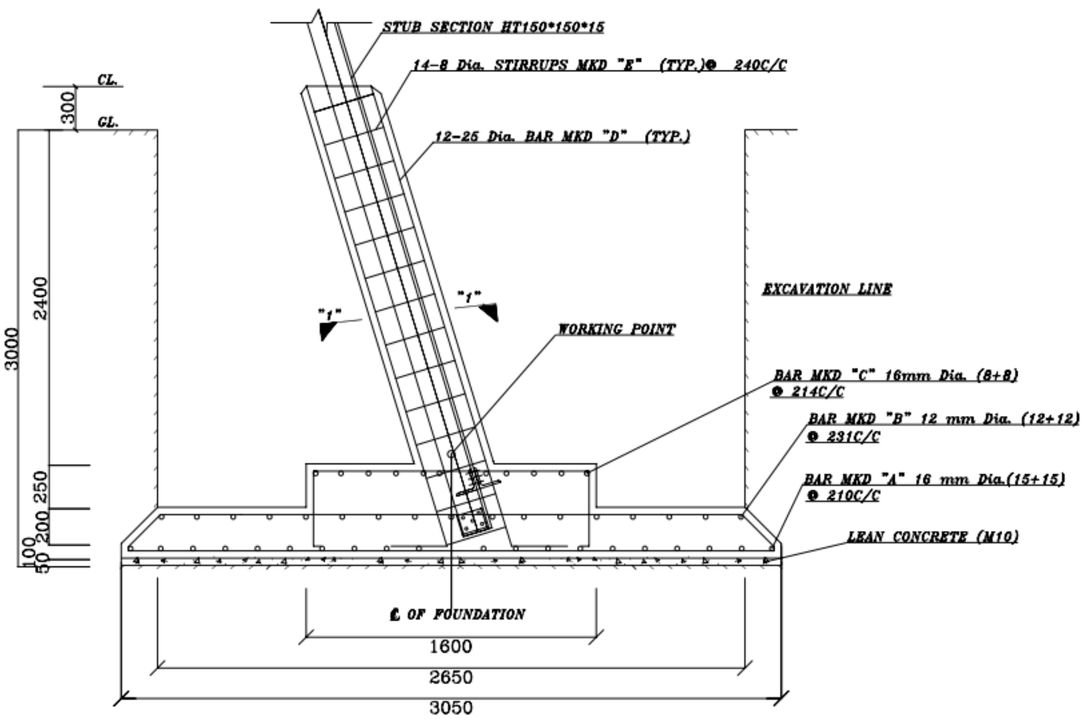
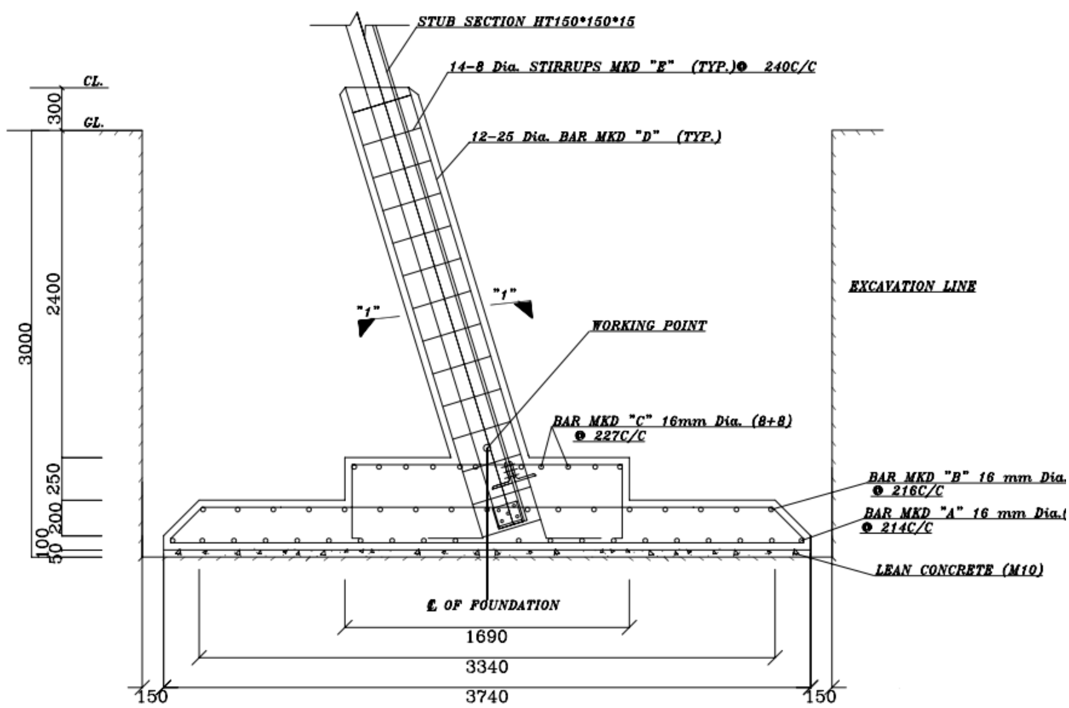
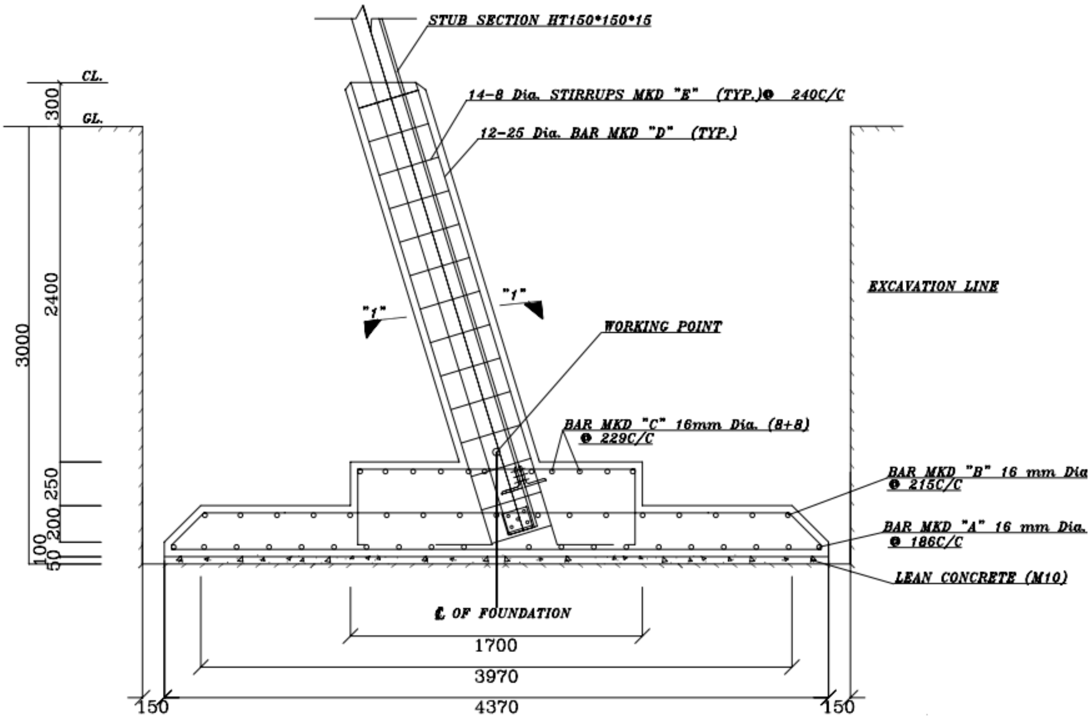
APPENDIX 01 – TYPE DRAWINGS ANALYZED TOWER FOUNDATIONS



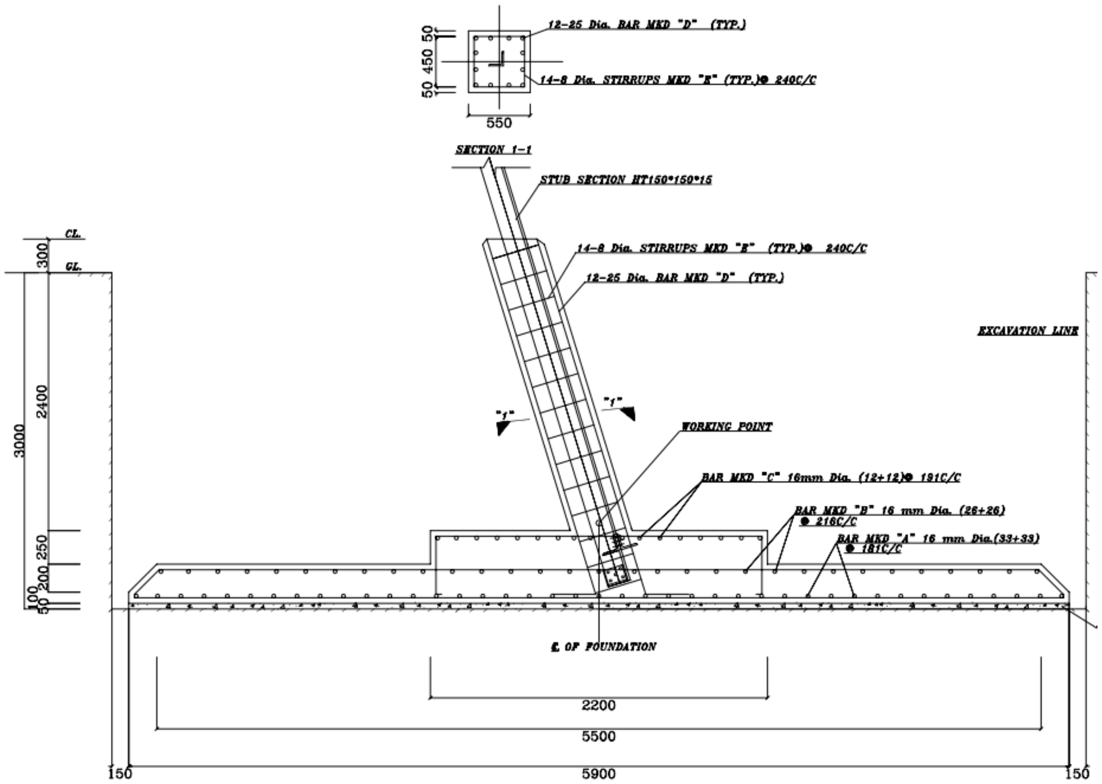
TD1 – S2 foundation



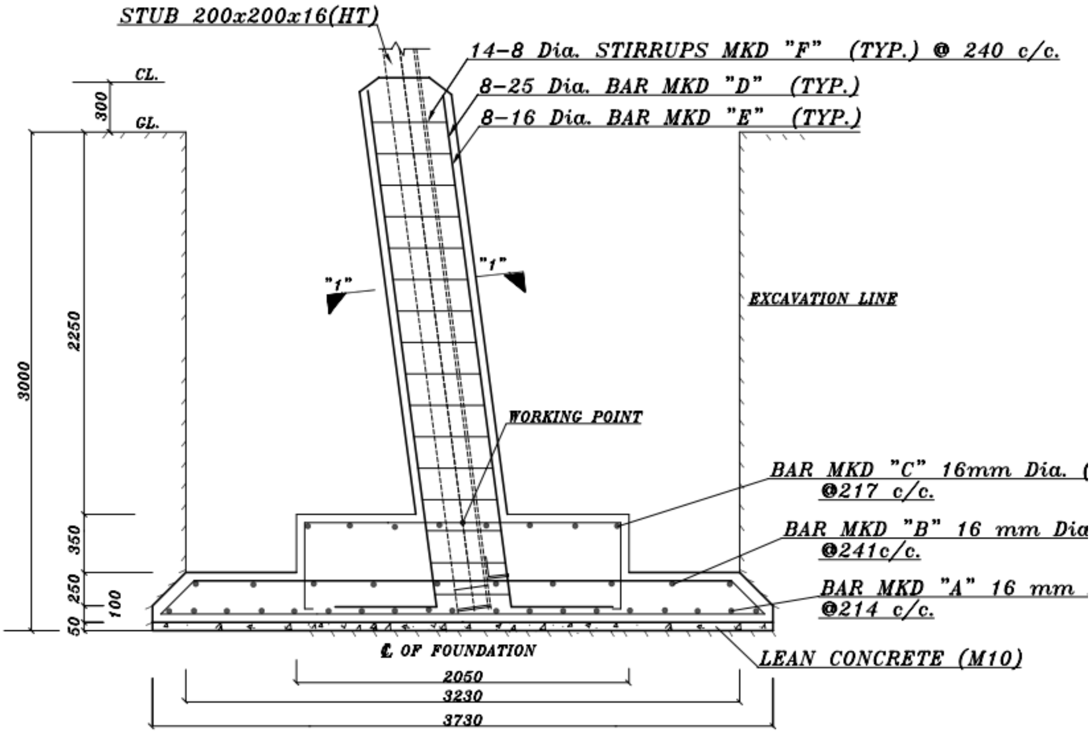
TD1 – S3 foundation



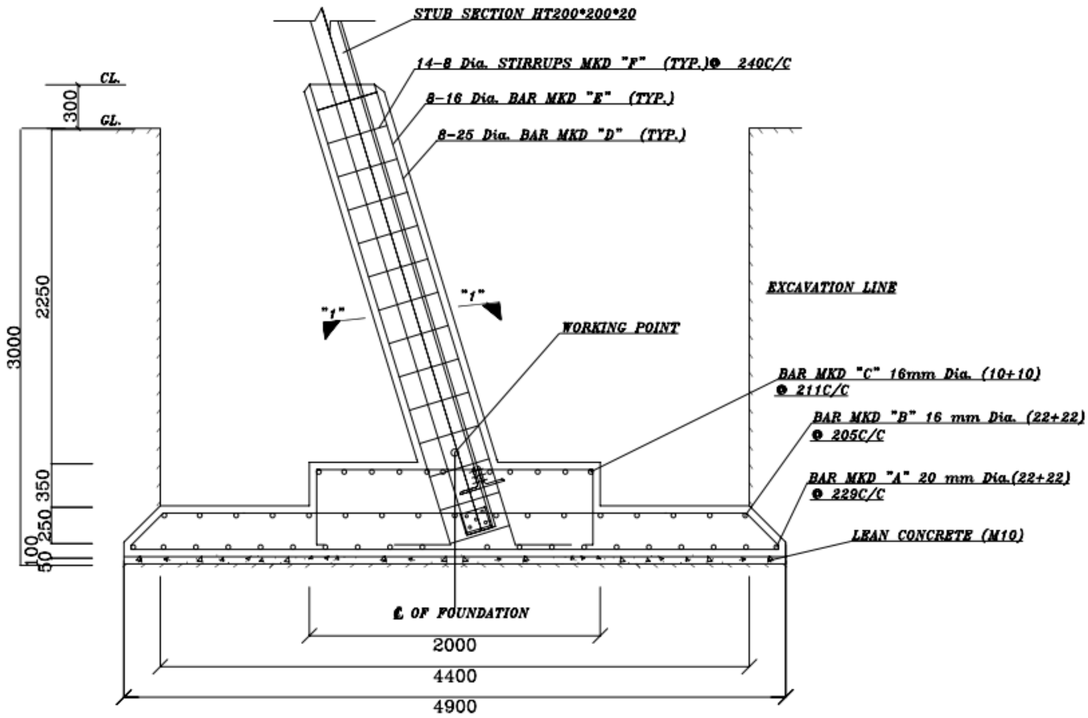
TD1 – S4 foundation



TD1 – S5 foundation



TD3-S2 foundation

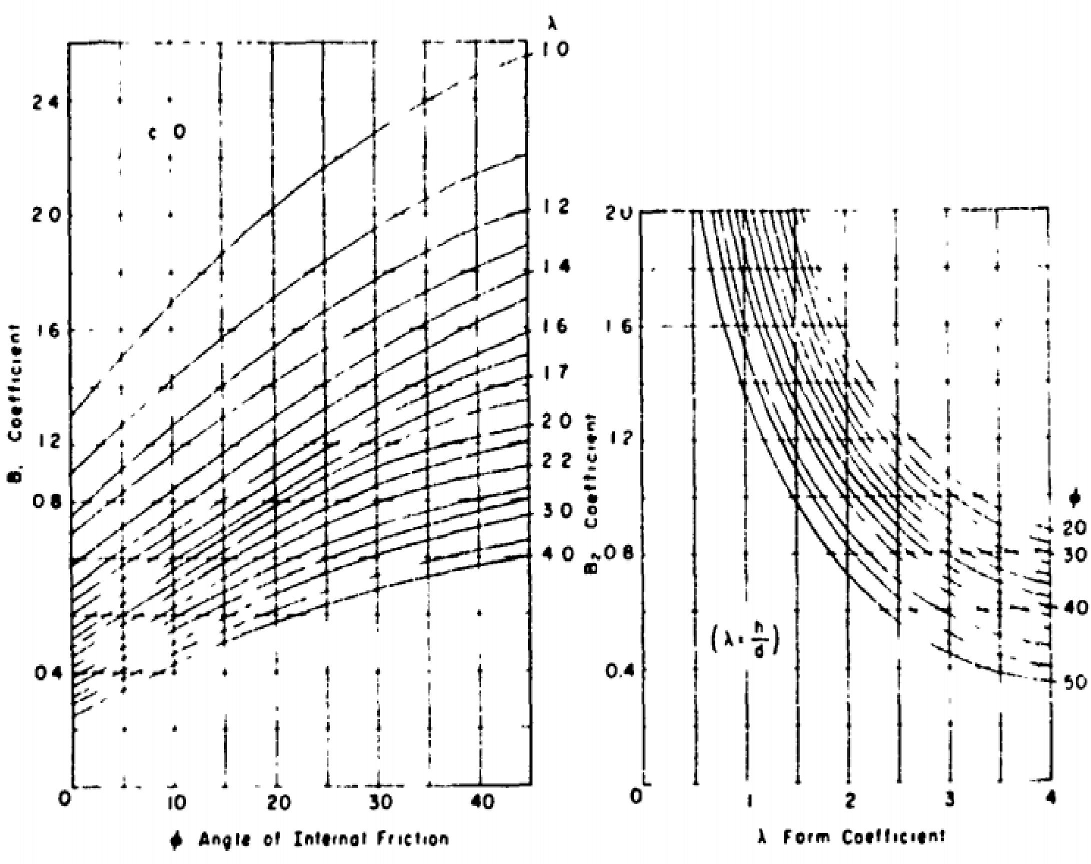


TD6 – S2 foundation

APPENDIX 02 – VALUE OF K_d FOR DEWBERRY METHOD

Class of Soil	K_d
Hardpan	1.2
Crumbly, damp	1.0
Firm, moist	0.8
Plastic, wet	0.7
Loose, dry	0.5

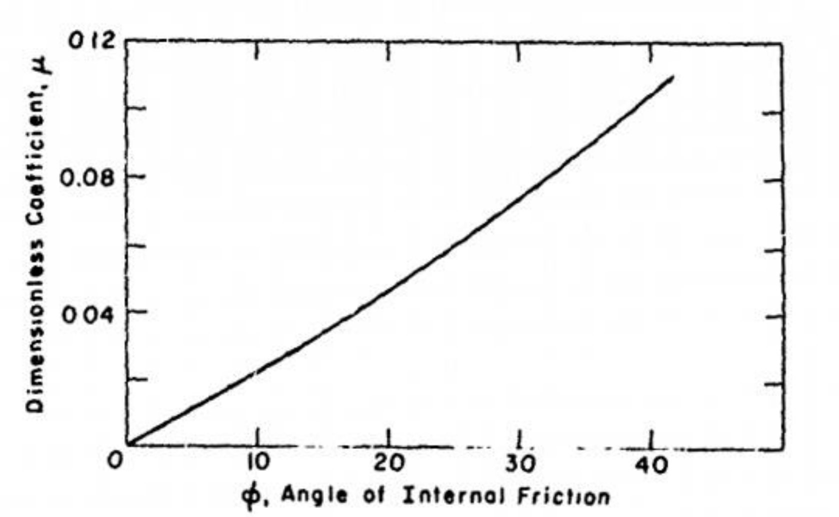
APPENDIX 03 – GRAPHS TO DETERMINE BALLA'S COEFFICIENTS B_1 AND B_2



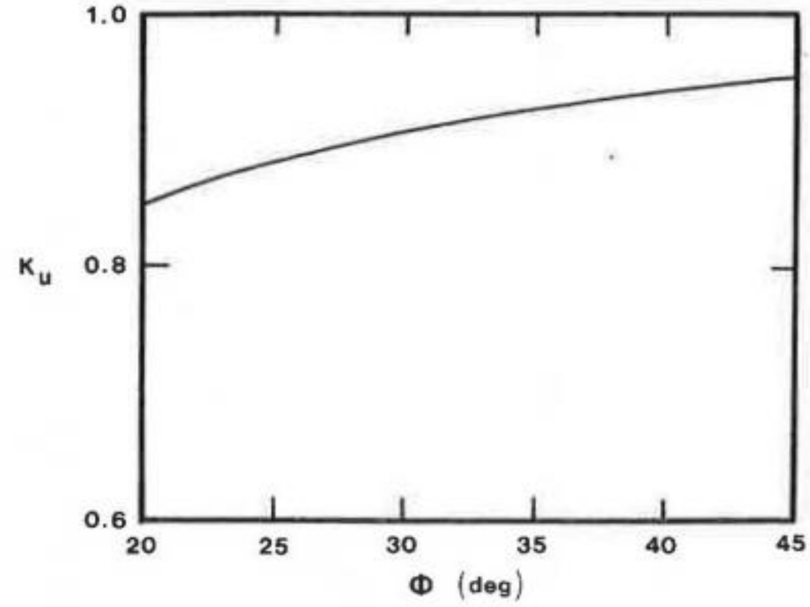
APPENDIX 04 – PULLOUT STRENGTH FACTORS K_1, K_2, K_3 AND K_4 FOR MATSUO AND TAGAWA METHOD

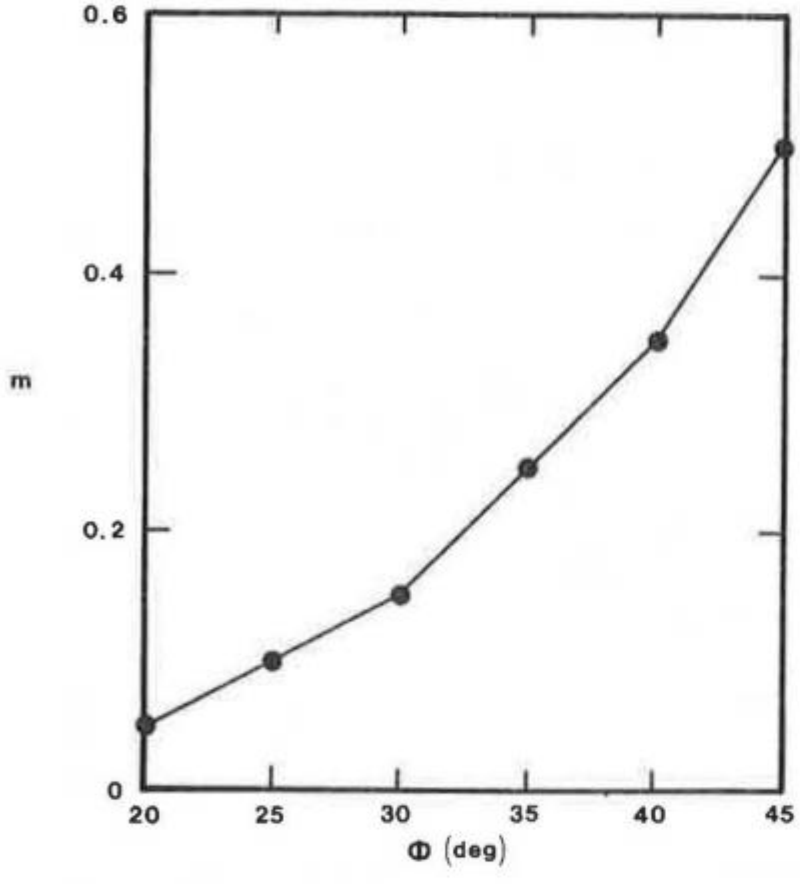
(h_2/R) limit	K_1	K_2	K_3	K_4
$0.5 \leq \frac{h_2}{R} \leq 1$	$0.056\phi + 4.0$	$0.007\phi + 1.0$	$0.027\phi + 7.653$	$0.002\phi + 1.052$
$1 \leq \frac{h_2}{R} \leq 3$	$0.056\phi + 4.0$	$0.016\phi + 1.1$	$0.027\phi + 7.653$	$0.004\phi + 1.103$
$3 \leq \frac{h_2}{R} \leq 10$	$0.597\phi + 10.4$	$0.023\phi + 1.3$	$0.013\phi + 6.110$	$0.005\phi + 1.334$

APPENDIX 05 – DIMENSIONLESS FUNCTION μ OF MARIUPOL'SKII METHOD



APPENDIX 06 – SHAPE FACTOR COEFFICIENT AND UPLIFT COEFFICIENT FOR MAYERCHOF AND ADAMS METHOD





APPENDIX 07 – VALUE FOR FACTOR f_c AND K_0 FOR MORS METHOD

Class of Soil	f_c	
	Smooth surface	**Rough Surface**
Moist clay and loam	0.2	0.3
Dry sand	0.6	0.7
Wet sand	0.3	0.5
Gravel	0.4	0.5

K_0 = 0.35 – 0.60 for sand and gravel

K_0 = 0.45 – 0.70 for normally consolidated clay and silt

K_0 = 0.80 – 1.36 for over-consolidated clays

APPENDIX 08 – VALUE FOR FACTOR j FOR MORS METHOD

$$j = 13\ for\ anchor\ grillage\ in\ compacted\ backfill$$

$$j = 10\ for\ formed\ concrete\ footings\ without\ base\ in\ gravel$$

$$j = 5\ for\ formed\ concrete\ footings\ with\ base\ in\ gravel$$

$$j = 1\ for\ concrete\ footings\ poured\ against\ stiff\ clay$$

APPENDIX 08 – FACTORS $M_{c0}, M_{\varphi0}$ AND $M_{\gamma0}$ FOR BIAREZ AND BARRAUD METHOD