BEARING CAPACITY - SHEAR CRITERION

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BEARING CAPACITY – SHEAR CRITERIA

ABSTRACT

Determination of bearing capacity of soil is paramount for the design of foundations. There are several analytical methods available for the computation of bearing capacity. Only the shear criterion for bearing capacity is considered for this project.

This study includes bearing capacity calculation for both shallow and deep foundations by different methods. Terzaghi's, Meyerhof's, Vesic's and Hansen's methods are used for shallow foundations. It will incorporate the effects of groundwater table, eccentric loading and stratified soil on the bearing capacity of the foundations. For deep foundations γ-z method and USACE method are used. The structural design of continuous wall footing is also included.

An android application will be developed using the information based on this study, to calculate the bearing capacity of soil and design wall footings.

DEDICATION

We dedicate this dissertation to our parents. Without their patience, understanding, support, and most of all love, the completion of this work would not have been possible. Also to Dr. Kamran Akhtar who came up with the idea for this application.

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KEY TO SYMBOLS AND ABBREVIATIONS

α = base inclination angle; adhesion factor

A' = effective area

$A_{surface}$ = surface area of the pile

β = ground inclination angle

b_c, b_q, b_γ = base inclination factors

B = width of the footing

B' = effective width

c = cohesion

d = diameter of the pile

d, D_1, D_2, D_w = depths of water table

d_b = diameter of the bar

D_f = depth of footing

e = eccentricity

e_r = eccentricity along radius

E_g = efficiency factor for group piles

f = surface friction

f_y = yield strength of steel

f_c = compressive strength of concrete

FS = factor of safety

GWT = groundwater table

g_c, g_q, g_γ = ground inclination factors

ɣ = modified unit weight of soil for water table

γ' = effective unit weight of soil

γ_w = unit weight of water

γ_{sat} = saturated unit weight of soil

γ = unit weight of soil

H = depth of soil layer

H' = depth to weaker layer

H_i = horizontal component of inclined load

i_c, i_q, i_γ = load inclination factors

$K_{p\gamma}$ = passive earth pressure

K_s = coefficient of friction for sand

L = length of footing

L' = effective length

l_d = development length of dowels

λ_{cs}, λ_{qs}, $\lambda_{\gamma s}$ = shape factors

λ_{cd}, λ_{qd}, $\lambda_{\gamma d}$ = depth factors

λ_{ci}, λ_{qi}, $\lambda_{\gamma i}$ = load inclination factors

M = moment acting on footing

M_u = bending moment of footing

m = no. of rows of piles

N_q, N_c, N_γ = bearing capacity factors

N_q^*, N_c^* = bearing capacity factors of piles

n = no. of piles in a row

p_v = effective overburden pressure

P = vertical point load

φ = internal angle of friction

φ = strength reduction factor

q_o = total overburden pressure

q_u = ultimate bearing pressure

q_u' = unconfined compressive strength

q_a = allowable bearing pressure

q_{tip} = tip resistance per unit area

q_1 = ultimate tip resistance in the strong layer

q_2 = ultimate tip resistance in the weak layer

$Q_{ultimate}$ = ultimate pile capacity

Q_{tip} = tip resistance of pile

$Q_{surface}$ = skin resistance of pile

Q = total vertical load

R = radius of circular footing

s_c, s_q, s_γ = shape factors

s = center to center spacing between piles

σ_h' = effective horizontal earth pressure

$\theta = \tan^{-1}(d / s)$; load inclination angle

$\tan\delta$ = coefficient of friction

V_i = vertical component of inclined load

z = variable depth

CHAPTER 1

INTRODUCTION

1.1 General

Loads from a structure are transferred to the soil through a foundation. Foundation itself is a structure, often constructed from concrete, steel or wood. An important task for a geotechnical engineer is to use the knowledge of properties of soils and their response to loadings to design foundations.

A geotechnical engineer must ensure the following two stability conditions are satisfied:

- The foundation must not collapse or become unstable under any conceivable loading. This is called ultimate limit state.
- Settlement of the structure must be within tolerable limits so as to not impair the design function of the structure.

Both the settlement and the resistance to shear failure depend on the size and shape of the foundation or footing, its depth below the surface and the properties of the soil it rests upon. In designing a foundation both these failures are examined.

There are three types of shear failures:

- General shear failure
- Local shear failure
- Punching shear failure

There are two types of settlements:

- Elastic settlement
- Consolidation settlement

1.2 Importance

In selecting a type of foundation, one has to consider the functions of the structure and the load it has to carry, the subsurface condition of the soil, and the cost of the superstructure.

Design loads also play an important part in the selection of the type of foundation. The various loads that are likely to be considered are:

- Dead loads
- Live loads

- Wind and earthquake forces
- Lateral pressures exerted by the foundation earth on the embedded structural elements
- The effects of dynamic loads
- Lateral or uplift forces on the foundation elements due to high water table
- Swelling pressures on the foundations in expansive soils
- Heave pressures on foundations in areas subjected to frost heave
- Negative frictional drag on piles where pile foundations are used in highly compressible soils.

1.3 Foundation Types

There are two types of foundations:

- Shallow foundations
- Deep foundations

1.3.1 Shallow Foundations

A shallow foundation is a type of foundation which transfers structural loads to the earth very near the surface, rather than to a subsurface layer or a range of depths. It is a customary practice to regard a foundation shallow if the depth to width ratio is less than or equal to 2.5. Shallow foundations include spread footing foundations, mat-slab foundations, slab-on-grade foundation, pad foundations, rubble trench foundations and earth-bag foundations.

1.3.2 Deep Foundations

A deep foundation is a type of foundation which transfers building loads to the earth farther down from the surface than a shallow foundation does, to a subsurface layer or a range of depths. A pile is a vertical structural member of deep foundations.

1.4 Bearing Capacity

Bearing capacity is the capacity of soil to support the loads applied to the ground. The bearing capacity of soil is the maximum average contact pressure between the foundation and the soil which should not produce shear failure in the soil.

There is no method for obtaining the bearing capacity of soil but as an estimate by different theoretical solutions. Some of the key terms used in computation of bearing capacity are as follows:

1.4.1 Total Overburden Pressure, q_o

q_o is the intensity of total overburden pressure due to weight of the soil above the footing and water at the base of the level of the foundation.

1.4.2 Ultimate Bearing Capacity, q_u

q_u is the bearing capacity of soil at which it fails under shear.

1.4.3 Allowable Bearing Capacity, q_a

q_a is the bearing capacity at which a foundation is designed. It is expressed as,

$$q_a = \frac{q_u}{FS} \quad \text{.... (1.1)}$$

CHAPTER 2

BEARING CAPACITY OF SHALLOW FOUNDATIONS

2.1 General

Bearing capacity depends on the shape, size and depth of the foundation resting on the soil, as well as the properties of the soil it rests upon. To calculate the ultimate bearing capacity of shallow foundations the following presented their solutions,

- Terzaghi (1943)
- Meyerhof (1963)
- Hansen (1960)
- Vesic (1973-75)

2.2 Terzaghi's Bearing Capacity Theory

Terzaghi used the same form of equation as proposed by Prandtl (1921) and extended his theory to take into account the weight of soil and the effect of soil above the base of the foundation on the bearing capacity of soil. He developed his model for strip footing, that is, the depth to width ratio approaches zero, and modified his equation for different foundation shapes.

2.2.1 Bearing Capacity Equations

For strip footing,

$$q_u = cN_c + qN_q + 0.5B\gamma N_\gamma \quad \ldots. (2.1)$$

Here, c is cohesion, q is surcharge loading, B is the width of footing and N_c, N_q and N_γ are bearing capacity factors, expressed by,

$$N_c = (N_q - 1)\cot\varphi \quad \ldots. (2.2)$$

$$N_q = [e^{(0.75\pi - \varphi/2)\tan\varphi}] / [2\cos^2(45^o + \varphi/2)] \quad \ldots. (2.3)$$

$$N_\gamma = 0.5\tan\varphi\,(K_{p\gamma} / \cos^2\varphi) - 1 \quad \ldots. (2.4)$$

Here, $K_{p\gamma}$ is the passive earth pressure given by,

$$K_{p\gamma} = (1 + \sin\varphi) / (1 - \sin\varphi) \quad \ldots. (2.5)$$

For square footing,

$$q_u = 1.3\,cN_c + qN_q + 0.4B\gamma N_\gamma \quad \ldots. (2.6)$$

For circular footing,

$$q_u = 1.3\, cN_c + qN_q + 0.3B\gamma N_\gamma \quad .... (2.7)$$

For rectangular footing,

$$q_u = [1 + 0.3\,(B / L)]\, cN_c + qN_q + 0.5B\gamma N_\gamma\, [1 - 0.2\,(B / L)] \quad .... (2.8)$$

2.3 Meyerhof's Bearing Capacity Theory

Meyerhof presented a solution similar to Terzaghi, but he included shape, depth and inclination factors for cohesion, friction and surcharge terms.

Load inclination angle is the angle in degrees to which the load P is inclined to the centroid of the footing. It is denoted by θ and is shown below,

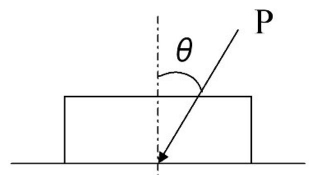


Figure 1. Load Inclination Angle θ (Bowles, 1997)

2.3.1 Bearing Capacity Equations

The Meyerhof's equation is expressed as:

$$q_u = c\, \lambda_{cs}\, \lambda_{cd}\, \lambda_{ci}\, N_c + q\, \lambda_{qs}\, \lambda_{qd}\, \lambda_{qi}\, N_q + 0.5B\gamma\, \lambda_{\gamma s}\, \lambda_{\gamma d}\, \lambda_{\gamma i}\, N_\gamma \quad .... (2.9)$$

Here, the N_c, N_q and N_γ are bearing capacity factors, and λ_{cs}, λ_{cd}, λ_{ci}, λ_{qs}, λ_{qd}, λ_{qi}, $\lambda_{\gamma s}$, $\lambda_{\gamma d}$ and $\lambda_{\gamma i}$ are shape, depth and inclination factors.

Bearing capacity factors are given as,

If $\varphi = 0$, then $N_c = 5.14$, otherwise,

$$N_q = e^{(\pi \tan\varphi)} \tan^2 [45^o + (\varphi / 2)] \quad .... (2.10)$$

$$N_c = (N_q - 1) \cot\varphi \quad .... (2.11)$$

$$N_\gamma = (N_q - 1) \tan (1.4\varphi) \quad .... (2.12)$$

Shape factors are given as,

If $\varphi = 0$, then $\lambda_{qs} = \lambda_{\gamma s} = 1$, $\lambda_{cs} = 1 + 0.2\,(B / L)$, otherwise,

$$\lambda_{cs} = 1 + 0.2\,(B / L) \tan^2 [45^o + (\varphi / 2)] \quad .... (2.13)$$

$$\lambda_{qs} = \lambda_{\gamma s} = 1 + 0.1\,(B / L) \tan^2 [45^o + (\varphi / 2)] \quad .... (2.14)$$

Here, L is the length of the footing.

Depth factors are given as,

If $\varphi = 0$, then $\lambda_{qd} = \lambda_{\gamma d} = 1$, $\lambda_{cd} = 1 + 0.2\ (D_f / B)$, otherwise,

$$\lambda_{cd} = 1 + 0.2\ (D_f / B) \tan [45^o + (\varphi / 2)] \quad \ldots.\ (2.15)$$

$$\lambda_{qd} = \lambda_{\gamma d} = 1 + 0.1\ (D_f / B) \tan [45^o + (\varphi / 2)] \quad \ldots.\ (2.16)$$

Inclination factors are given as,

$$\lambda_{ci} = [\ 1 - (\theta / 90^o)]^2 \quad \ldots.\ (2.17)$$

$$\lambda_{qi} = [\ 1 - (\theta / 90^o)]^2 \quad \ldots.\ (2.18)$$

$$\lambda_{\gamma i} = [\ 1 - (\theta / \varphi^o)]^2 \quad \ldots.\ (2.19)$$

2.4 Hansen's Bearing Capacity Theory

Hansen's solution is similar to Meyerhof's. Hansen included factors such as base inclination and ground inclination.

The base inclination angle is the angle in degrees to which the base of the footing is inclined on the soil. It is denoted by α. The ground inclination angle is the angle in degrees to which the soil profile is incline if the base of the footing rests near a slope. It is denoted by β. These are represented below,

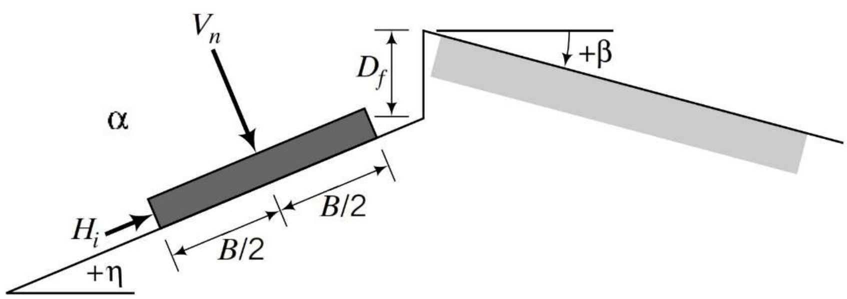


Figure 2. Base and Ground Inclination Angles, α and β (Bowles, 1997)

2.4.1 Bearing Capacity Equations

Hansen's equation is expressed as:

$$q_u = c\ s_c\ d_c\ g_c\ i_c\ b_c\ N_c + q\ s_q\ d_q\ g_q\ i_q\ b_q\ N_q + 0.5\ B\gamma\ s_\gamma\ d_\gamma\ g_\gamma\ i_\gamma\ b_\gamma\ N_\gamma \quad \ldots.\ (2.20)$$

Here, s_c, d_c, g_c, i_c, b_c, s_q, d_q, g_q, i_q, b_q, s_γ, d_γ, g_γ, i_γ and b_γ are the shape, depth, load inclination, base inclination and ground inclination factors.

Bearing capacity factors,

$$N_c = \text{(Same as Meyerhof)}$$

$$N_q = \text{(Same as Meyerhof)}$$

$$N_\gamma = 1.5\ (N_q - 1) \tan\varphi \quad \ldots.\ (2.21)$$

Shape factors are given by,

$$s_c = 1 + (B / L)(N_q / N_c) \quad .... (2.22)$$

$$s_q = 1 + (B / L) \tan\varphi \quad .... (2.23)$$

$$s_\gamma = 1 – 0.4 (B / L) \quad .... (2.24)$$

Depth factors are given by,

$$d_c = 1 + 0.4k \quad .... (2.25)$$

$$d_q = 1 + 2k \tan\varphi (1 – \sin\varphi)^2 \quad .... (2.26)$$

$$d_\gamma = 1$$

Here, for relatively shallower footings ($D / B \leq 1$), $k = D / B$.

For deeper footings ($D / B > 1$), $k = \tan^{-1}(D / B)$.

Ground inclination factors are given by,

$$g_c = 1 – (\beta / 147^o) \quad .... (2.27)$$

$$g_q = g_\gamma = [1 – 0.5 \tan\beta]^5 \quad .... (2.28)$$

Base inclination factors are given by,

$$b_c = 1 – (\alpha / 147^o) \quad .... (2.29)$$

$$b_q = e^{(-2\alpha \tan\varphi)} \quad .... (2.30)$$

$$b_\gamma = e^{(-2.7\alpha \tan\varphi)} \quad .... (2.31)$$

Load inclination factors are given by,

If $\varphi = 0$, $i_c = 1$, otherwise,

$$i_c = i_q – [(1 – i_q) / (N_q – 1)] \quad .... (2.32)$$

$$i_q = [1 – (0.5 \tan\theta)]^5 \quad .... (2.33)$$

$$i_\gamma = [1 – (0.7 \tan\theta)]^5 \quad .... (2.34)$$

2.5 Vesic's Bearing Capacity Theory

Vesic's solution is very similar to Hansen's solution. Difference is in some factors. Vesic also defined load inclination factors, ground inclination factors, base inclination factors in addition to shape and depth factors.

2.5.1 Bearing Capacity Equations

Vesic's equation is expressed as:

$$q_u = c\, s_c\, d_c\, g_c\, i_c\, b_c\, N_c + q\, s_q\, d_q\, g_q\, i_q\, b_q\, N_q + 0.5\, B\gamma\, s_\gamma\, d_\gamma\, g_\gamma\, i_\gamma\, b_\gamma\, N_\gamma \quad .... (2.35)$$

Here, s_c, d_c, g_c, i_c, b_c, s_q, d_q, g_q, i_q, b_q, s_γ, d_γ, g_γ, i_γ and b_γ are the shape, depth, load inclination, base inclination and ground inclination factors.

Bearing capacity factors,

$$N_c = \text{(Same as Meyerhof)}$$

$$N_q = \text{(Same as Meyerhof)}$$

$$N_\gamma = 2\,(N_q - 1)\tan\varphi \quad \text{…. (2.36)}$$

Shape factors are given by,

$$s_c = 1 + (B / L)(N_q / N_c) \quad \text{…. (2.37)}$$

$$s_q = 1 + (B / L)\tan\varphi \quad \text{…. (2.38)}$$

$$s_\gamma = 1 - 0.4\,(B / L) \quad \text{…. (2.39)}$$

Depth factors are given by,

$$d_c = 1 + 0.4k \quad \text{…. (2.40)}$$

$$d_q = 1 + 2k\tan\varphi\,(1 - \sin\varphi)^2 \quad \text{…. (2.41)}$$

$$d_\gamma = 1$$

Here, for relatively shallower footings ($D / B \leq 1$), $k = D / B$.

For deeper footings ($D / B > 1$), $k = \tan^{-1}(D / B)$.

Ground inclination factors are given by,

$$g_c = 1 - (\beta / 147^o) \quad \text{…. (2.42)}$$

$$g_q = g_\gamma = [1 - \tan\beta]^2 \quad \text{…. (2.43)}$$

Base inclination factors are given by,

$$b_c = 1 - (\alpha / 147^o) \quad \text{…. (2.44)}$$

$$b_q = b_\gamma = [1 - (\alpha\tan\varphi / 57^o)]^2 \quad \text{…. (2.45)}$$

Load inclination factors are given by,

If $\varphi = 0$, $i_c = 1$, otherwise,

$$i_c = i_q - [(1 - i_q) / (N_q - 1)] \quad \text{…. (2.46)}$$

$$i_q = [1 - \tan\theta]^2 \quad \text{…. (2.47)}$$

$$i_\gamma = [1 - \tan\theta]^3 \quad \text{…. (2.48)}$$

CHAPTER 3

SPECIAL CASES FOR SHALLOW FOUNDATIONS

3.1 General

Special cases that can be encountered while estimating bearing capacity may be groundwater table, stratified soil or eccentric loading. These three cases will be discussed in this chapter.

3.2 Effect of Groundwater Table

The solutions developed for estimating bearing capacity have been done under the assumption that groundwater table is absent. But if the groundwater table is present the soil properties undergo changes and uplift pressures are formed.

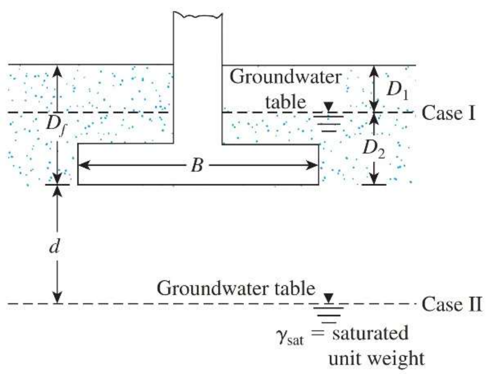


Figure 3. Modification of Bearing Capacity Equation for Water Table (Das, 2011)

3.2.1 Case I

If the water table is located such that $0 \leq D_1 \leq D_f$, the effective surcharge term q takes the form,

$$q = D_1\gamma + D_2 (\gamma_{sat} - \gamma_w) \quad .... (3.1)$$

3.2.2 Case II

If the water table is located such that $0 \leq d \leq B$, the effective surcharge is taken as,

$$q = \gamma D_f \quad .... (3.2)$$

In this case the γ term in the friction term of the bearing capacity equation takes the following form,

$$\bar{\gamma} = \gamma' + (d / B)(\gamma - \gamma') \quad .... (3.3)$$

3.2.3 Case III

If the water table is such that $d \geq B$, then water table has no effect on bearing capacity.

3.3 Stratified Soil

This case of soil profile is important because if the overlying layer of soil is stronger than the layers below it there is possibility of punching shear failure in the soil. Therefore, it is important the effect of layered soil is incorporated in the bearing capacity equation. This is usually done by weighted average method.

3.3.1 Variables Involved

To proceed to the estimation of bearing capacity for layered soils, we must define the terms that will be used. These are as follows,

- Foundation characteristics (B, L and D_f)
- Soil properties for different layers and their depths

3.3.2 Calculating Effective Depth

Effective depth helps in deciding which layers of soil are necessary for averaging out the soil properties.

We first need to calculate the depth where the failure is likely to occur. This is given by,

$$\text{Failure Depth} = B + D_f \quad .... (3.4)$$

Comparing the sum of the depths of the soil layers, starting with the lowest layer, with the failure depth, we select the layers whose sum is less than or equal to the failure depth, eliminating those below the failure depth.

3.3.3 Averaging Soil Properties

For the selected layers the following averages are used,

$$c_{av} = (c_1H_1 + c_2H_2 + c_3H_3 + ... + c_nH_n) / (\sum H_n) \quad .... (3.5)$$

$$\varphi_{av} = \tan^{-1} (H_1 \tan\varphi_1 + H_2 \tan\varphi_2 + H_3 \tan\varphi_3 + ... + H_n \tan\varphi_n) / (\sum H_n) \quad .... (3.6)$$

$$\gamma_{av} = (\gamma_1H_1 + \gamma_2H_2 + \gamma_3H_3 + ... + \gamma_nH_n) / (\sum H_n) \quad .... (3.7)$$

3.3.4 Estimating Bearing Capacity

Using the averaged out values for c, φ and γ in any bearing capacity equation of choice, the bearing capacity is calculated.

3.4 Eccentric Loading

Sometimes the foundations encounter moments in addition to concentric loads. These loads are called eccentric loads. To estimate bearing capacity for eccentrically loaded footings, we must estimate the amount of eccentricity in the loads. This is denoted by e. If the footing is loaded by some moment M, then eccentricity is given by,

$$e = (M / Q) \quad .... (3.8)$$

Here, Q is the total vertical loading on the footing.

We know foundations are of different shapes. For eccentricity studies we will consider the most common shapes which are strip, square, rectangular and circular.

3.4.1 Meyerhof's Effective Area Method

Meyerhof suggested that when a footing is subjected to eccentric loading the effective area must be calculated to give effective dimensions that can be later used to estimate the bearing capacity.

Depending on the direction of the eccentricity, twice the value e is subtracted from B or L.

$$L'' = L - 2e \qquad B'' = B \quad .... (3.9)$$

$$B'' = B - 2e \qquad L'' = L \quad .... (3.10)$$

The smaller of the two dimensions is taken as the effective width B' and the other dimension as the effective length L'.

Taking any bearing capacity equation of choice, following steps are followed,

- The effective width B' is used in the friction term of the equation
- B' and L' are used in computing shape factors

- Normal dimensions B and L are used for computing depth factors

This method is useful in calculating the bearing capacity of one way eccentrically loaded square, rectangular and strip footings.

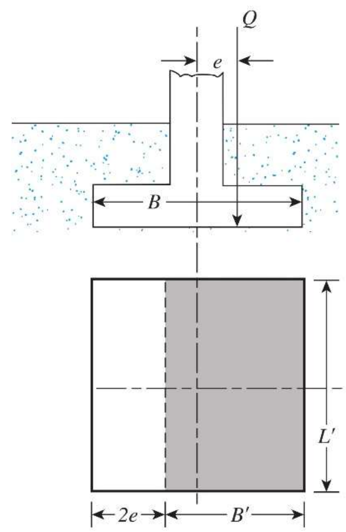


Figure 4. Eccentrically Loaded Footing (Das, 2011)

3.4.2 Highter and Anders' Method (From Das, 2011)

After studying different foundations under eccentric loads Highter and Anders published their work. It comprised of graphs for five possible cases that may arise under eccentrically loaded footings. These graphs give ratios of one dimension to its effective dimension which can then be multiplied with the existing dimension to give the effective length.

For circular footings, the effective area is shown as,

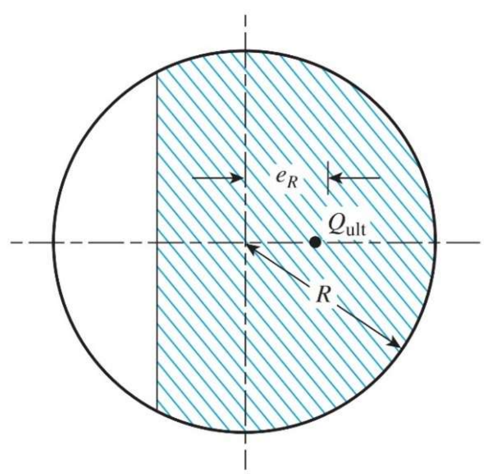


Figure 5. Circular Footing Under Eccentric Loading (Das, 2011)

The Highter and Anders graph for circular footing has been interpreted into a table as follows:

Table 1. Variation of A'/ R and B' / R with e_r / R

e_r / R	A'/ R	B' / R
0.1	2.8	1.85
0.2	2.4	1.32
0.3	2.0	1.2
0.4	1.61	0.8
0.5	1.23	0.67
0.6	0.93	0.5
0.7	0.62	0.37
0.8	0.35	0.23
0.9	0.12	0.12
1.0	0	0

The ratio of eccentricity value to the radius of the footing can be interpolated from this table and effective area and width can be found out. These value can then be used in any bearing capacity equation as described in the Meyerhof effective area method.

CHAPTER 4

BEARING CAPACITY FOR DEEP FOUNDATIONS

4.1 General

Deep foundations are used when shallow foundations are inadequate to bear the structural loads. Pile is a vertical structural element of deep foundations. Piles are made of concrete, steel and wood.

In addition to pile's strength itself, pile capacity is limited by the soil characteristics it rests on. The load carried by a pile is transmitted to the surrounding soil by,

- Friction or adhesion between the pile surface and the soil
- Load transmitted directly to the soil beneath the pile tip

The general equation for estimating pile capacity is given by,

$$Q_{ultimate} = Q_{tip} + Q_{surface} \quad \ldots. (4.1)$$

Here, $Q_{ultimate}$ is the ultimate bearing capacity of a single pile,

Q_{tip} is the resistance of the pile furnished by soil under pile's tip,

$Q_{surface}$ is the resistance of the pile furnished by friction or adhesion of the soil.

4.2 Pile Capacity in Sand

Soil pressure generally increases with depth, however it has been determined that in sands the effective overburden pressure of soil adjacent to the pile does not increase after a certain level of penetration is reached. Below this depth, called the critical depth D_c, the pressure remains constant.

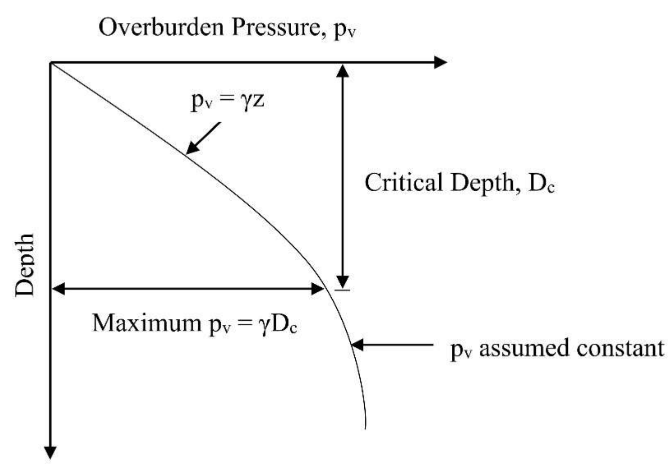


Figure 6. Effective Overburden Pressure Variation with Depth (Evett, 2008)

The critical depth depends upon field condition of the sand and size of the pile. Tests have indicated that it ranges from 10 to 20 pile diameters depending on the density of the sand.

The resistance offered by sand to the pile are expressed as,

$$Q_{tip} = q_{tip} \times A_{tip} \quad .... (4.2)$$

$$Q_{surface} = f \times A_{surface} \quad .... (4.3)$$

4.2.1 Skin Resistance

To find the skin resistance offered to the pile we need the effective horizontal earth pressure on the pile. It is given by,

$$\sigma'_h = \gamma \cdot z \cdot K_s \quad .... (4.4)$$

So we can write $Q_{surface}$ as,

$$f \times A_{surface} = (\text{Pile Circumference})(\text{Area under } p_v \text{ diagram})(K_s \times \tan\delta) \quad .... (4.5)$$

K_s varies with the density of the soil and material of the pile. It can be taken from the table below,

Table 2. K_s Values for different densities and Material (Evett, 2008)

Ks		
Material	Low	High
Wood	1.5	4
Concrete	1	2
Steel (Smooth)	0.5	1
Steel (Rusted)	0.5	1
Steel (Corrugated)	0.5	1

tanδ is coefficient of friction between sand and pile material. It can be taken by the following table,

Table 3. tanδ For Different Pile Material (Evett, 2008)

Coefficient of Friction For Sand	
Material	tanδ
Concrete	0.45
Wood	0.4
Steel(Smooth)	0.2
Steel(Rusted)	0.2
Steel(Corrugated)	tanφ

4.2.2 Tip Resistance

The tip resistance is a function of effective vertical overburden pressure. It is given by,

$$q_{tip} = p_v \times N_q^* \quad .... (4.6)$$

$$p_v = \gamma D_c \quad \ldots. (4.7)$$

N_q^* is a bearing capacity factor, that can be obtained from the table below,

Table 4. N_q^* For Sand (Evett, 2008)

N_q^* Factors For Sand	
Phi	N_q^*
25	10
30	20
35	50
40	135
45	350

4.3 Pile Capacity in Clay

Pile capacity in clay differs from sand as the skin resistance is provided by adhesion between the pile shaft and soil and the tip resistance is offered by cohesion in the soil.

4.3.1 Skin Resistance

Skin resistance offered by clay can be expressed as,

$$f \times A_{surface} = \alpha \cdot c \cdot A_{surface} \quad \ldots. (4.8)$$

α is adhesion factor, which can be determined by using unconfined compressive strength of the soil by the following table,

Table 5. Adhesion Factor, α (Evett, 2008)

Adhesion Factor	
q_u' (ton/ft^2)	α
0	1
0.5	0.95
1	0.84
1.5	0.68
2	0.55
2.5	0.46
3	0.43

4.3.2 Tip Resistance

Tip resistance offered by clay can be expressed as,

$$q_{tip} = cN_c^* \quad \ldots. (4.9)$$

Here, c is cohesion and N_c^* is a bearing capacity factor usually taken as 9.

4.4 Pile Capacity in c-φ Soil

c-φ soil has both cohesion and internal friction. It possesses both characteristics of sand and clay.

4.4.1 Skin Resistance

Skin resistance for a c-φ soil is expressed as,

$f \text{ x } A_{surface} = (\text{Pile Circumference})(\text{Area under } p_v \text{ diagram})(K_s \tan\delta) + \alpha \cdot c$ …. (4.10)

4.4.2 Tip Resistance

Tip resistance for a c-φ soil is expressed as,

$$q_{tip} = p_v N_q^* + cN_c^* \quad \text{…. (4.11)}$$

4.5 Pile Group Capacity

Piles are almost always arranged in group of three or more. These are tied together by a pile cap which is attached to the head of individual piles and consequently cause several piles to act as a pile foundation.

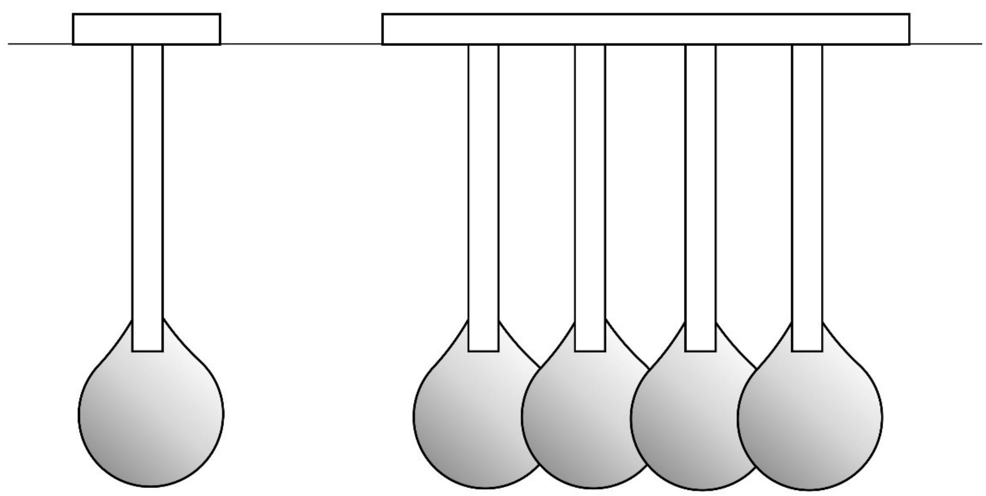


Figure 7. Pile Group Stress Zone (Evett, 2008)

When piles are driven close together the soil stresses caused by individual piles overlap and cause the bearing capacity of the foundation to be less than the sum of pile capacities for individual piles. Pile group capacity is given by,

$$Q_{ultimate} = (\text{Total no. of piles})(\text{Effiency factor})(Q_{tip} + Q_{surface}) \quad \text{…. (4.12)}$$

4.5.1 Converse Labarre Equation for Efficiency Factor

The converse Labarre equation gives an efficiency factor that can be used to estimate pile group capacity. It is expressed as,

$$E_g = 1 - \theta\,[\{(n-1)\,m + (m-1)\,n\} / (90\,m \times n)] \quad \ldots.\ (4.13)$$

Here, $\theta = \tan^{-1}(d / s)$,

m is the no. of rows of piles,

n is the no. of piles in a row,

d is diameter of the piles,

s is spacing between piles from center to center, usually taken as s =3.25 d.

CHAPTER 5

SPECIAL CASES FOR DEEP FOUNDATION

5.1 General

Special cases that can be encountered in estimating the pile capacity can be water table and stratified soil. These two cases will be discussed in this chapter.

5.2 Effect of Groundwater Table

Groundwater table induces heaving or uplift pressure. In case of pile foundations, the effective overburden pressure decreases due to pore water pressure.

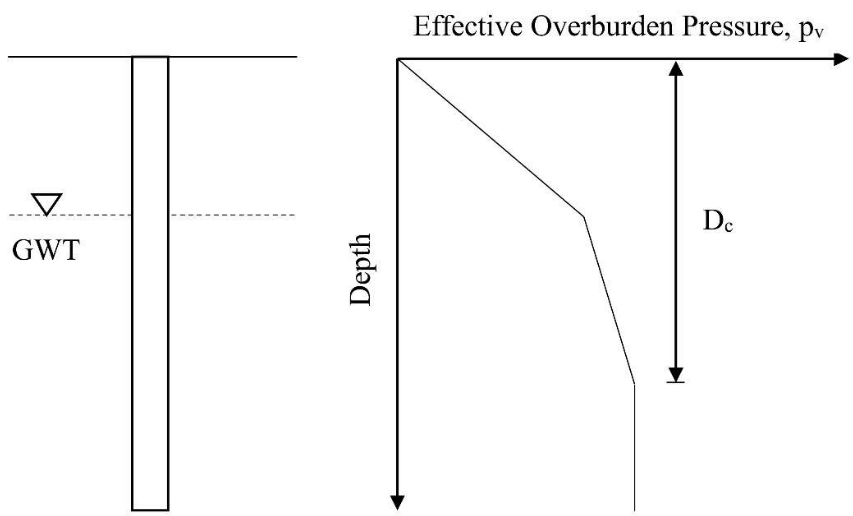


Figure 8. Effect of Groundwater Table on Piles (Evett, 2008)

5.2.1 Effect in Sand

Let D_w be the depth of the water table from the ground surface. When computing p_v and area under p_v diagram, the pressure will change due to upward pressure exerted by the groundwater table. So when computing p_v when we reach the groundwater table, we use $\gamma' = (\gamma - \gamma_w)$.

From the diagram above for the first length of the curve, p_v is given by,

$$p_v = \gamma D_w \quad \text{.... (5.1)}$$

The second length is effected by groundwater table, so p_v is given by,

$$p_v = \gamma' (D_c - D_w) \quad \text{.... (5.2)}$$

After the critical depth is reached p_v becomes constant.

5.2.2 Effect in Clay

Clay have very poor permeability, due to which groundwater movement through them is extremely slow to the extent that it has no effect on the pile capacity.

5.3 Stratified Soil

It is normal for piles to be extended through a number of different strata. The pile capacity for such a case can be expressed by the following equation,

$$Q_{ultimate} = q_{tip} \times A_{tip} + \sum f \times A_{surface} \quad \text{…. (5.3)}$$

5.3.1 Skin Resistance

There are different depths of different layers. So, skin resistance for each layer and depth is calculated according to the soil properties and summed up.

5.3.2 Tip Resistance

The tip resistance for the layer in which the pile tip rests is calculated. Although when calculating p_v and area under p_v diagram, all the different unit weights and water table if present will be taken into account.

5.3.3 Modification for Punching Shear

If the pile tip rests on a layer which overlays a weaker layer then there is a possibility that punching shear failure will occur in the weaker soil.

Meyerhof suggested modification in the equation of pile tip resistance. It is given as,

$$q_{tip} = q_2 + (q_1 - q_2) H' / 10d \leq q_1 \quad \text{…. (5.4)}$$

Here, d is the diameter of the pile, H' is the thickness between the tip of the pile and the top of the weaker layer, q_2 is the ultimate tip resistance in the weak layer, q_1 is the ultimate tip resistance in the strong layer.

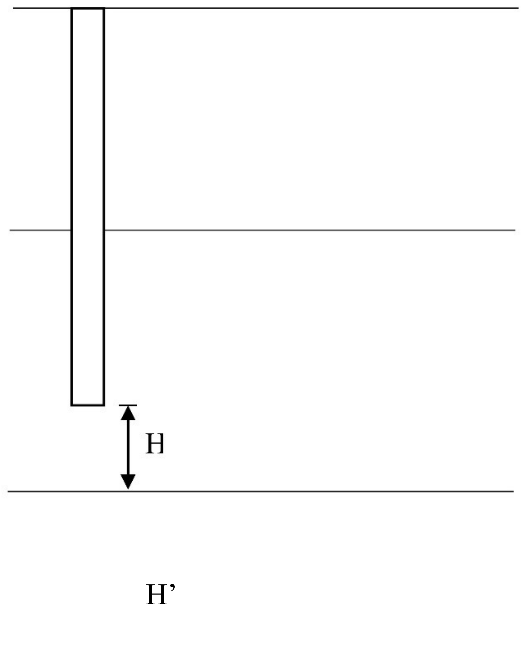


Figure 9. Pile In Layered Soil (Evett, 2008)

CHAPTER 6

WALL FOOTING DESIGN

6.1 General

Footings are structural members used to support columns and walls and to transmit and distribute their loads to the soil in such a way that the load bearing capacity of the soil is not exceeded, excessive settlement, differential settlement, or rotation are prevented and adequate safety against overturning or sliding is maintained.

6.1.1 Wall Footings

A wall footing cantilevers out on both sides of the wall. The soil pressure causes the cantilevers to bend upward, and as a result, reinforcement is required at the bottom of the footing. The critical sections for design for flexure and anchorage are at the face of the wall. One-way shear is critical at a section a distance d from the face of the wall. The presence of the wall prevents two-way shear. Thicknesses of wall footings are chosen in 1-in. increments, widths in 2 or 3-in. increments.

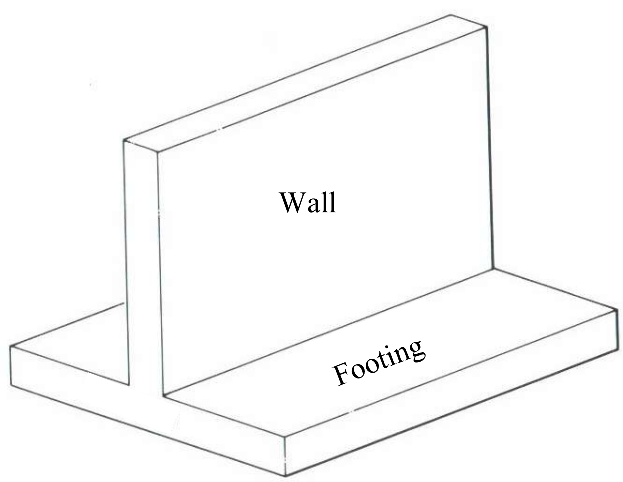


Figure 10. Wall Footing (MacGregor, 2012)

6.2 Design Considerations

Footings must be designed to carry the loads and transmit them to the soil safely while satisfying code limitations.

- Bearing capacity of columns at their base

- Dowel requirements
- Development length of bars
- Differential settlement

6.3 Steps of Designing

1. Estimate size of footing and factored net pressure

   Area = Total load (including self-weight) / Allowable soil pressure …. (6.1)

   $$q_u = P_u \text{ / Area of footing} \quad …. (6.2)$$

   Here,

   q_u = bearing pressure

   P_u = actual load

2. Check one-way shear

The ultimate shearing force can be calculated as:

$$V_u = q_u\, b\, (L/2 - c/2 - d) \quad …. (6.3)$$

Here,

V_u = shear force

q_u = bearing pressure for strength design

d = depth of reinforcement

c = side cover

If no shear reinforcement is to be used, then d can be checked, assuming

$V_u = \varphi V_c$

$$d = V_u / 2\varphi b f_c^{0.5} \quad …. (6.4)$$

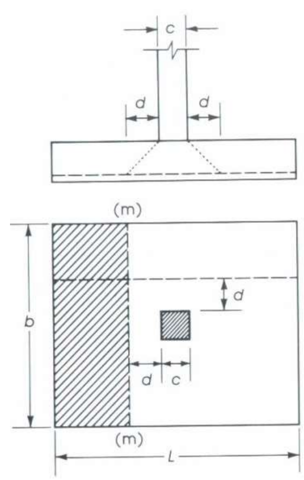


Figure 11. Check for One-way Shear (MacGregor, 2012)

3. Design reinforcement

Next step is to calculate the area of steel required.

$$A_s = M_u / \varphi f_y (d - a/2) \quad …. (6.5)$$

$$a = f_y A_s / 0.85 f_c b \quad …. (6.6)$$

Here,

A_s = area of steel

M_u = bending moment of footing

f_y = yield strength of steel

f_c = compressive strength of concrete

4. Check development length

Dowel bars must be checked for proper development length.

$$l_d = 0.02 f_y d_b / f_c^{0.5} \quad …. (6.7)$$

Here,

l_d = development length of dowels

d_b = diameter of the bar

CHAPTER 7

METHODOLOGY

7.1 General

All the information gathered in the past chapters will be utilized in developing an android application. In this age of smartphones, an application that serves to calculate bearing capacity for soils under different cases will be the best tool a geotechnical engineer can ask for. Also this application will estimate wall footing design.

7.2 Life Cycle

The application development life cycle consisted of the following stages,

7.2.1 Initiation

The development of smartphones have led to applications developed for different departments and fields of sciences. In geotechnical engineering, foundation analysis and design is the most common problem that is faced. The opportunity to develop an application for solution to such problems faced by engineers emerged, and a proposal to develop the application was forwarded and approved.

7.2.2 System Concept Development

The scope for the project is as below

"To develop and application to calculate shear bearing capacity and wall footing reinforcement design."

Different aspects were under consideration to make the application as user friendly as possible.

A user guide was also planned to be included for engineers using the application for the first time.

7.2.3 Planning

The development on the application was divided into the following phases,

- Logic development
- Spreadsheet development
- Android application development

7.2.4 Design

The design stage comprised of the following phases,

- The blueprints for the user interface design were made using internet portal FluidUI.
- Logics were developed through thorough literature review.
- Spreadsheets were developed for calculation and verification (Shown in Appendix A).

7.2.5 Development

Using android studio and IntelliJ IDEA development on the application began. Along with developing user interface by modifying the FluidUI concept drawings, C# was used to develop the logical calculations running on the back end of the application (Shown in Appendix B).

7.2.6 Verification and Testing

This will be discussed in the upcoming chapter.

7.2.7 Implementation

The android application developed will be published in standard APK (.apk) format on Google Playstore for a nominal charge as compensation for all the man hours put into its development.

7.2.8 Operations and Maintenance

As the users for application will increase different bugs will need fixes to be made and published for the application that were not previously detected. Also we plan to incorporate bearing capacity calculator for settlement criterion over time.

CHAPTER 8

VERIFICATION AND TESTING

8.1 General

Every software development lifecycle involves the stage of verification and testing, that verifies and quantifies the accuracy of the software in performing the task that it was developed for. For the application we developed, we tested the spreadsheets first for errors or discrepancies. Using these spreadsheets, an application was developed. The application was then tested for the results.

8.2 Verification Files

Following are the verification files we used to test our application.

8.2.1 Shallow Foundations

For testing the application for shallow foundations we separately tested it for following conditions.

8.2.1.1 Single Layered Concentric Loading

For these conditions we used the following examples,

- Example 15.1, Page no. 519, Das B. M. Principles of Geotechnical Engineering (Thomson, 2006)

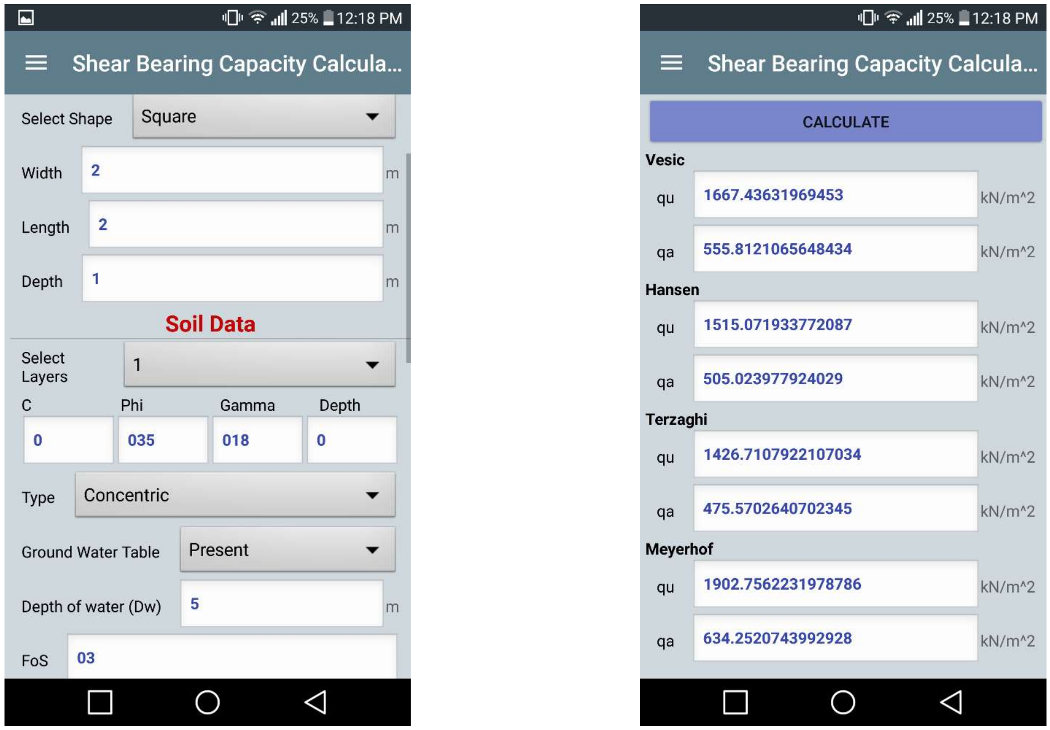


Figure 12. Solved Example 15.1 (Application)

- Example 12.2, Page no. 437, Budhu M. Soil Mechanics and Foundations (Wiley, 2010)

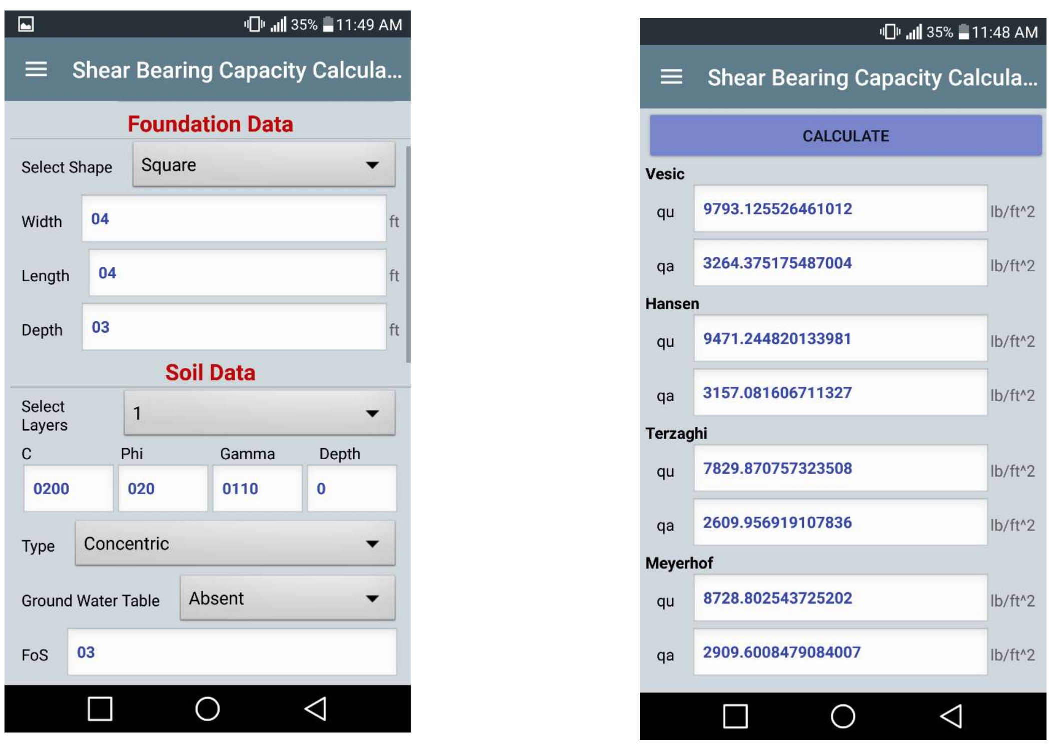


Figure 13. Solved Example 12.2 (Application)

8.2.1.2 Single Layered Eccentric Loading

For these conditions we used the following examples,

- Example 3.5, Page no. 163, Das B. M. Principles of Foundation Engineering (Cengage Learning, 2011)

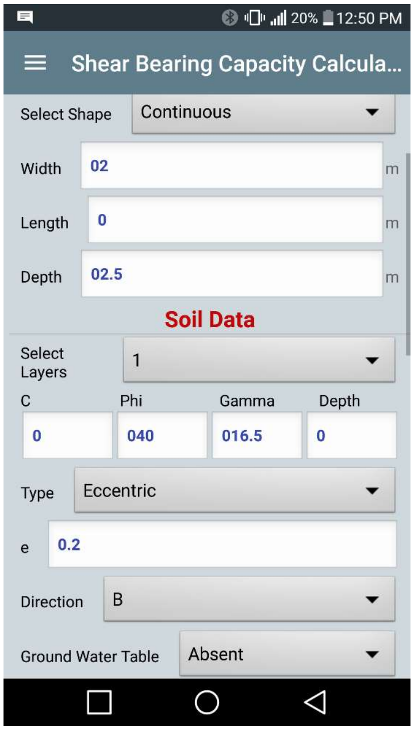


Figure 14. Solved Example 3.5 (Application)

8.2.2 Deep Foundations

For testing the application for deep foundations we separately tested it for following conditions.

8.2.2.1 Single Layered

For this condition we used the following examples,

- Example 10-1, Page no. 338, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

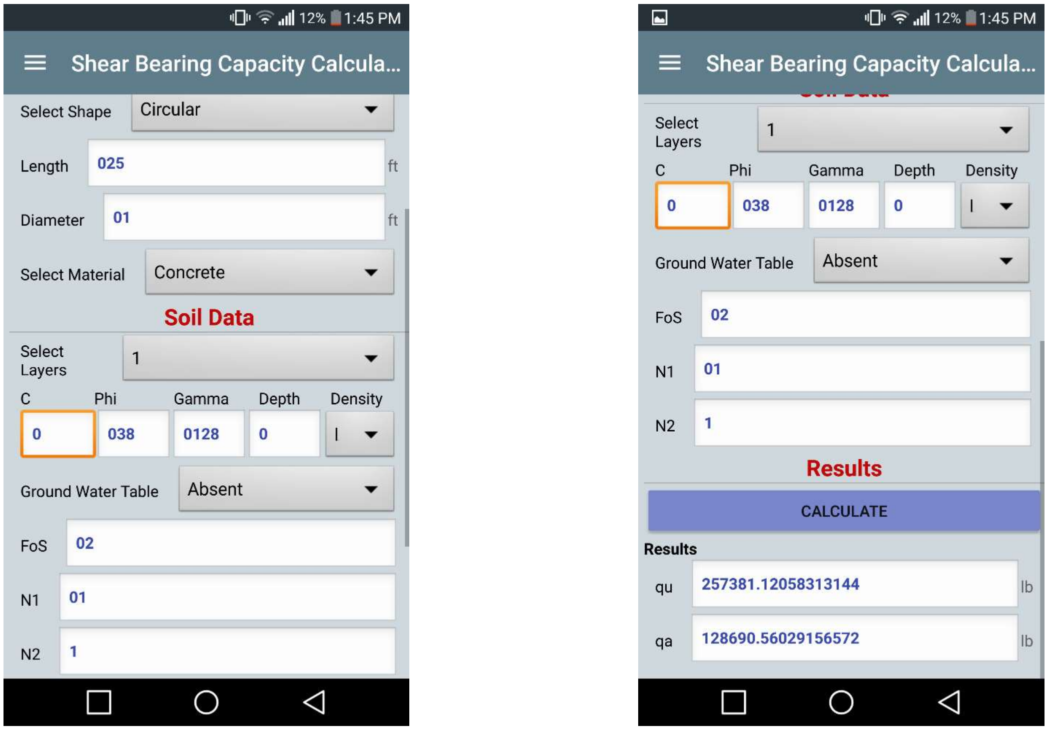


Figure 16. Solved Example 10-1 (Application)

- Example 10-2, Page no. 339, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

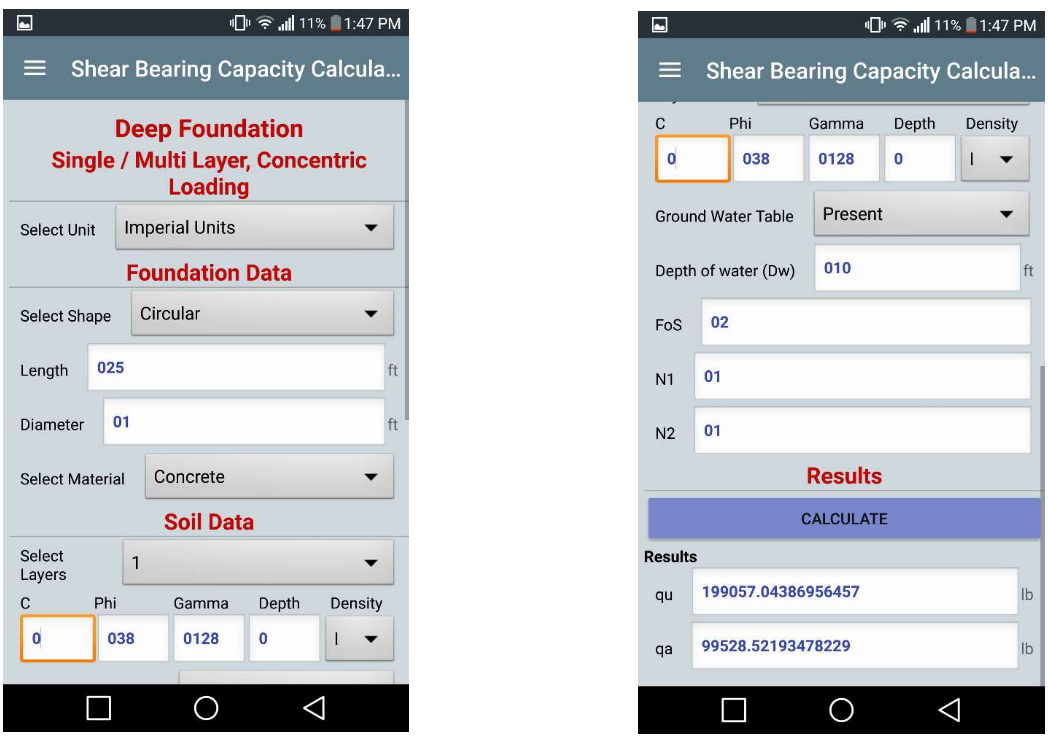


Figure 15. Solved Example 10-2 (Application)

8.2.2.2 Multilayered

For this condition we used the following example,

- Example 10-4, Page no. 347, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

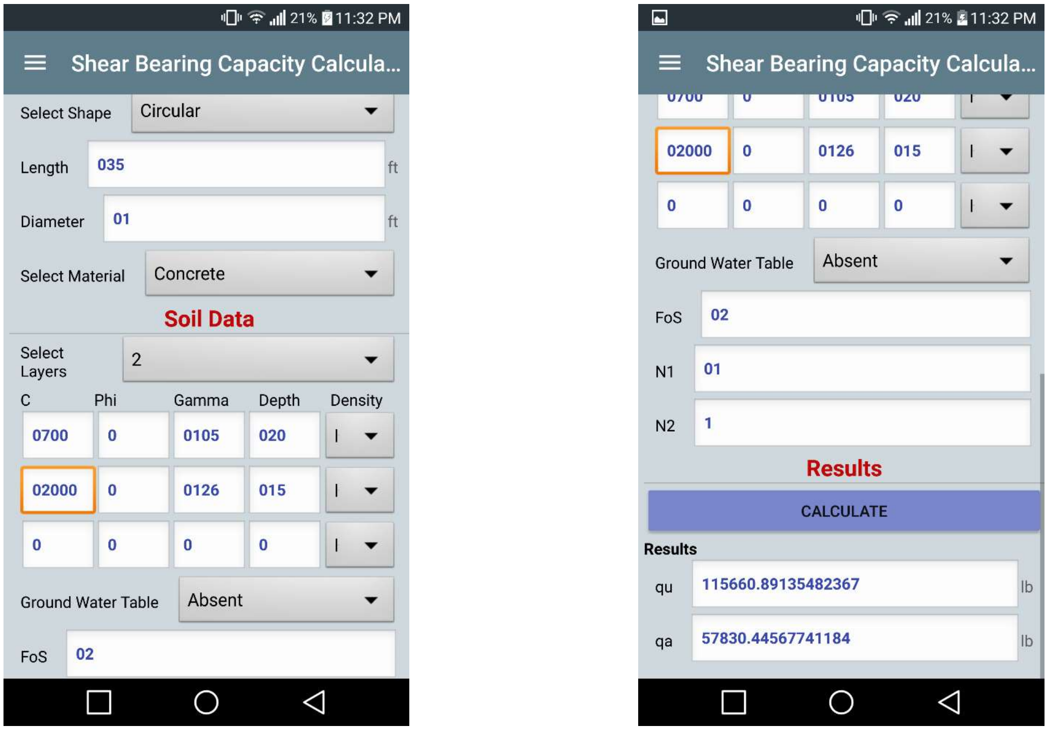
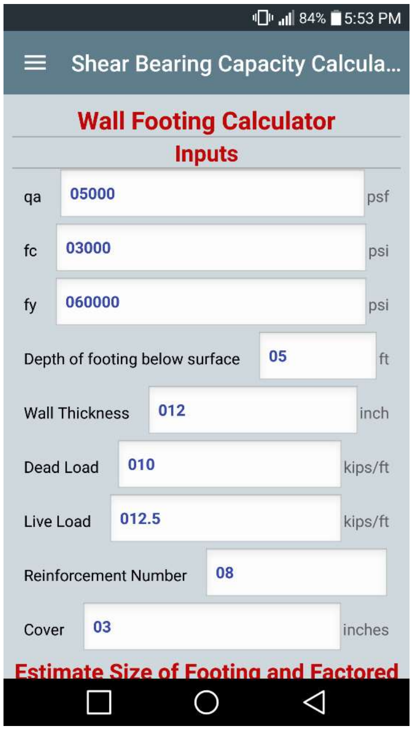


Figure 17. Solved Example 10-4 (Application)

8.2.3 Wall Footing Design

For wall footing design we used the following example,

- Example 15-1, Page no. 827, MacGregor J. G., Wight J. K., Reinforced Concrete Mechanics and Design (Prentice Hall, 2011)



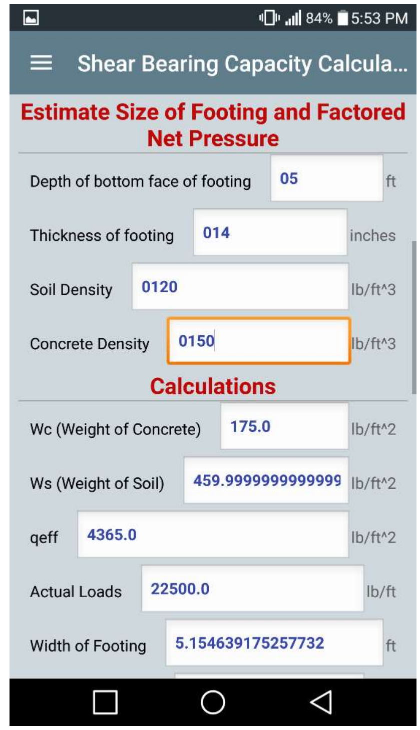
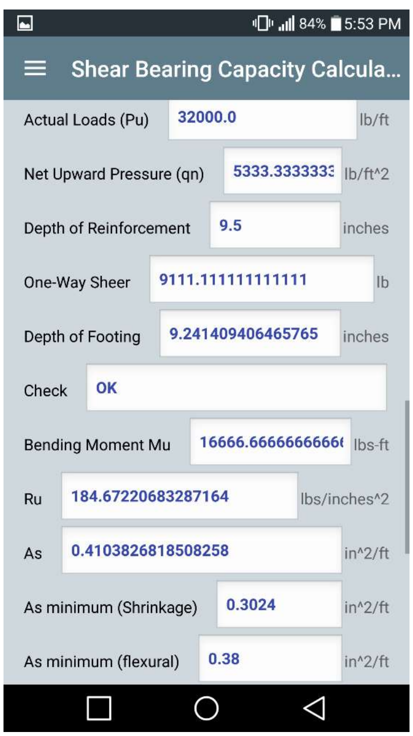


Figure 19. Solved Example 15-1 (Application) Part I



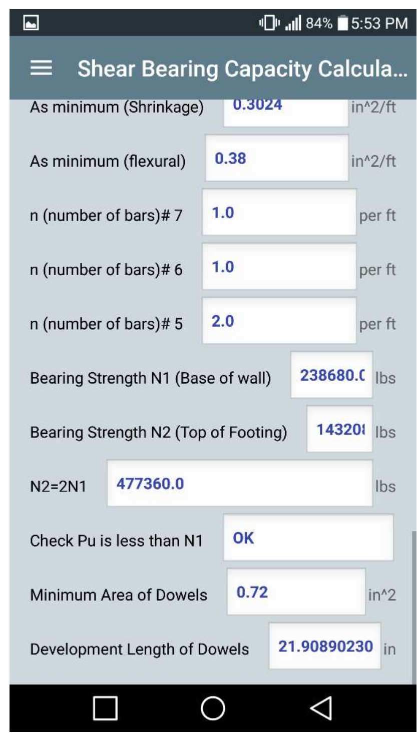


Figure 18. Solved Example 15-1 (Application) Part II

8.3 Comparison of Application and Hand Calculation

8.3.1 Shallow Foundations

For these foundations we used the following examples,

- Example 15.1, Page no. 519, Das B. M. Principles of Geotechnical Engineering (Thomson, 2006)

  Hand Calculated = 1424 kN/m^2 Application = 1426.7 kN/m^2
- Example 12.2, Page no. 437, Budhu M. Soil Mechanics and Foundations (Wiley, 2010)

  Hand Calculated = 7830 kN/m^2 Application = 7829.87 kN/m^2
- Example 3.5, Page no. 163, Das B. M. Principles of Foundation Engineering (Cengage Learning, 2011)

  Hand Calculated = 3350 kN/m^2 Application = 3352.4 kN/m^2

The small differences that can be noticed are due to the fact that application uses established equations rather than charts or graphs to determine bearing capacity factors.

8.3.2 Deep Foundations

For this condition we used the following examples,

- Example 10-1, Page no. 338, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

  Hand Calculated = 258800 lbs Application = 257381 lbs
- Example 10-2, Page no. 339, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

  Hand Calculated = 187000 lbs Application = 199057 lbs
- Example 10-4, Page no. 347, Liu C., Evett J. B., Soils and Foundations (Prentice Hall, 2008)

  Hand Calculated = 115201 lbs Application = 115660.89 lbs

The small differences that can be noticed are due to the fact that application uses established equations rather than charts or graphs to determine bearing capacity factors. Also for multilayered soil it factors it off for punching shear.

8.3.3 Wall Footing Design

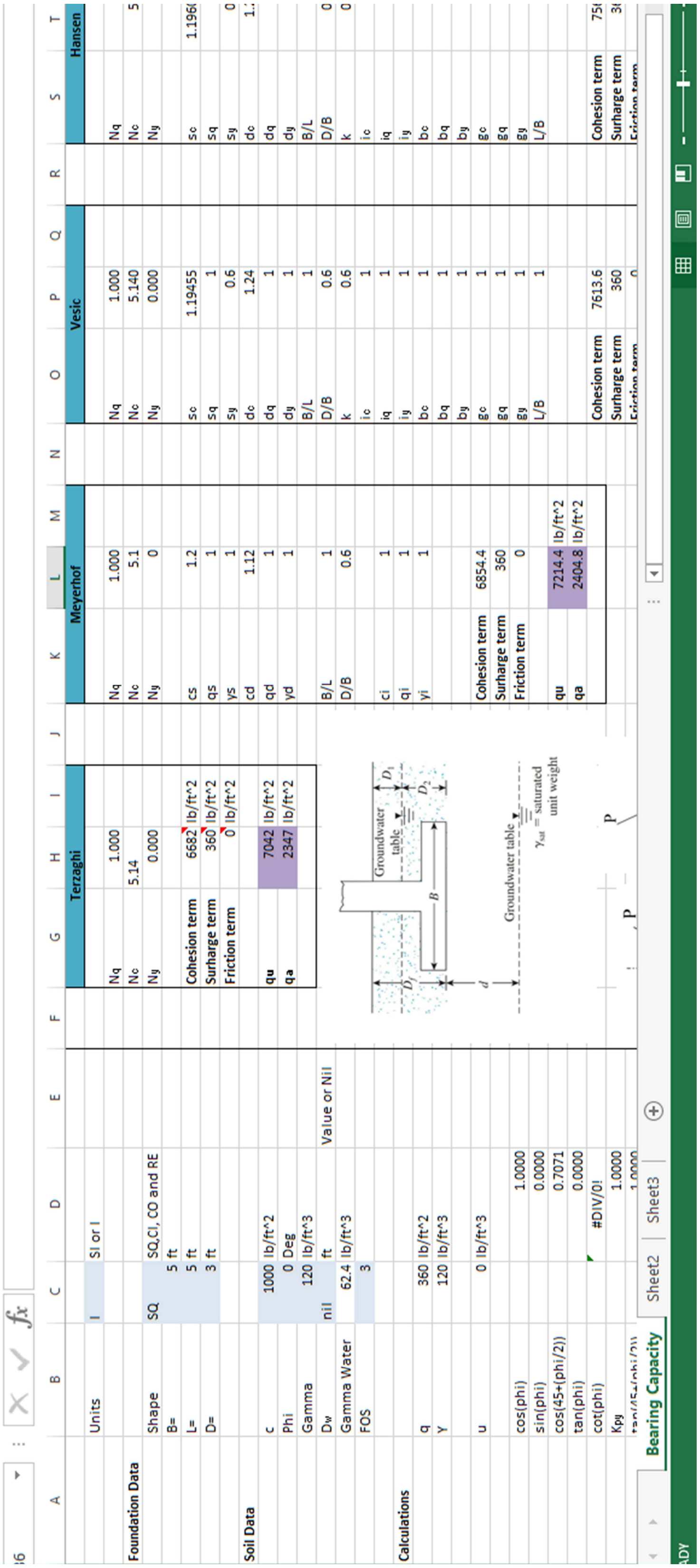
For wall footing design we used the following example,

- Example 15-1, Page no. 827, MacGregor J. G., Wight J. K., Reinforced Concrete Mechanics and Design (Prentice Hall, 2011)

The values change according to the designer's view of the appropriate size of footing.

APPENDICES

Appendix A



	Units	I	SI or I	
Foundation Data				
	Shape	SQ	SQ,CI, CO and RE	
	B=	5	ft	
	L=	5	ft	
	D=	3	ft	
Soil Data				
	c	1000	lb/ft^2	
	Phi	0	Deg	
	Gamma	120	lb/ft^3	
	Dw	nil	ft	Value or Nil
	Gamma Water	62.4	lb/ft^3	
	FOS	3		
Calculations				
	q	360	lb/ft^2	
	Y	120	lb/ft^3	
	u	0	lb/ft^3	
	cos(phi)		1.0000	
	sin(phi)		0.0000	
	cos(45+(phi/2))		0.7071	
	tan(phi)		0.0000	
	cot(phi)		#DIV/0!	
	Kpy		1.0000	

Terzaghi		
Nq	1.000	
Nc	5.14	
Ny	0.000	
Cohesion term	6682	lb/ft^2
Surharge term	360	lb/ft^2
Friction term	0	lb/ft^2
qu	7042	lb/ft^2
qa	2347	lb/ft^2

Meyerhof		
Nq	1.000	
Nc	5.1	
Ny	0	
cs	1.2	
qs	1	
ys	1	
cd	1.12	
qd	1	
yd	1	
B/L	1	
D/B	0.6	
ci	1	
qi	1	
yi	1	
Cohesion term	6854.4	
Surharge term	360	
Friction term	0	
qu	7214.4	lb/ft^2
qa	2404.8	lb/ft^2

Vesic	
Nq	1.000
Nc	5.140
Ny	0.000
sc	1.19455
sq	1
sy	0.6
dc	1.24
dq	1
dy	1
B/L	1
D/B	0.6
k	0.6
ic	1
iq	1
iy	1
bc	1
bq	1
by	1
gc	1
gq	1
gy	1
L/B	1
Cohesion term	7613.6
Surharge term	360
Friction term	0

Hansen	
Nq	
Nc	5
Ny	
sc	1.196
sq	
sy	0
dc	1.
dq	
dy	
B/L	
D/B	0
k	0
ic	
iq	
iy	
bc	
bq	
by	
gc	
gq	
gy	
L/B	
Cohesion term	75
Surharge term	3
Friction term	

Bearing Capacity | Sheet2 | Sheet3

Appendix B

Due to the right of protection of intellectual property, a small portion of the programming done in the application is shown,

```
public void getData(double widthBx,double lengthLx,double diameterDx,double depthDx,
double cohesionCx,double phiPx,double gammasoilx,double depthwaterDWx,double FoSx,double gammaConcx,
double theetaTx,double directionsDx,double alphaAx,double betaBx,double gammawaterx,double eccentricityx,
        if (selected_type.contains("Concentric")){
            widthB=widthBx;
            lengthL=lengthLx;
        }else {
            if (selected_shape.contains("Circular")){
                selected_shape="Rectangular";
            }
            double[]
BLmat=calculateEccentricity(widthB,lengthL,diameterD,eccentricity);
            widthB=BLmat[0];
            lengthL=BLmat[1];
        }
    }
    public void calculateTerzaghi(){
        double Nq=0,Nc=0,Ny=0,cohesion=0,surcharge=0,friction=0,q=0,gamma=0;
            //Calculate Nq
            Nq = (Math.exp(2 * (0.75 * Math.PI - ((Math.toRadians(phiP)) / 2)) * Math.tan(Math.toRadians(phiP)))) / (2 * (Math.pow(Math.cos(Math.toRadians(45) + (Math.toRadians(phiP) / 2)), 2)));
            //Calculate Nc
            if (phiP == 0) {
                Nc = 5.14;
            } else {
                Nc = 1 / Math.tan(Math.toRadians(phiP)) * (Nq - 1);
            }
            //Calculate Ny
            Ny = (2 * (Nq + 1) * Math.tan(Math.toRadians(phiP))) / (1 + (0.4 * Math.sin(4 * Math.toRadians(phiP))));
```

```
//Calculate cohesion
if (selected_shape.contains("Continuous")) {
   cohesion = cohesionC * Nc;
} else if (selected_shape.contains("Rectangular")) {
   cohesion = ((1+0.3(widthB/lengthL)) * cohesionC * Nc);
} else {
   cohesion = .3 * cohesionC * Nc;
}
//Calculate q
if (selected_dw.contains("Absent")) {
   q = (gammasoil * depthD);
} else {
   if (depthwaterDW <= depthD) {
      q = (depthwaterDW * gammasoil) + ((depthD - depthwaterDW) *
(gammasoil - gammawater));
   } else {
      q = gammasoil * depthD;
   }
}
//Calculate surcharge
if (selected_shape.contains("Rectangular")) {
   surcharge = q * Nq;
} else {
   surcharge = q * Nq;
}
//Calculate Gamma
if (selected_dw.contains("Absent")) {
   gamma = gammasoil;
} else {
   if (depthwaterDW <= depthD) {
      gamma = (gammasoil - gammawater);
   } else if ((depthwaterDW - depthD) <= widthB) {
      gamma = (gammasoil - gammawater) + ((depthwaterDW -
depthD)/widthB)) * (gammasoil-(gammasoil - gammawater));
```

```
    } else {
        gamma = gammasoil;
    }
}
//Calculate Friction
if (selected_shape.contains("Circular")) {
    friction = 0.3 * diameterD * gamma * Ny;
} else if (selected_shape.contains("Rectangular")) {
    friction = 0.5 * widthB * gamma * Ny * (1-0.2*(widthB/lengthL));
} else if (selected_shape.contains("Square")) {
    friction = 0.4 * widthB * gamma * Ny;
} else {
    friction = 0.5 * widthB * gamma * Ny;
}
terAvail=true;
ter_qu = cohesion + surcharge + friction;
ter_qa = ter_qu / FoS;
```

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