HAMK
Häme University
of Applied Sciences

Comparing bearing capacity of shallow foundations methods

Bachelor’s Thesis
Construction engineering degree program
Spring 2025
Farbod Ghiasi

HAMK
Häme University
of Applied Sciences

Abstract

DP Construction engineering degree programme
Author Farbod Ghiasi Year 2025
Subject Comparing bearing capacity of shallow foundations methods
Supervisors Elis Kivi

Shallow foundations play a critical role in transferring structural loads to the underlying soil while ensuring stability and minimizing settlement. This bachelor's thesis provides a comprehensive comparison of methods for determining the bearing capacity of shallow foundations, encompassing theoretical, empirical, and code-based approaches to guide practical engineering design.

The study starts by outlining the several types of shallow foundations such as pad footings, strip footings, combined footings, cantilever footings, and mat foundations and divides them from deep foundations. It then explains key concepts like ultimate and allowable bearing capacity, different modes of shear failure (general, local, and punching), as well as the factors that influence them, including type of soil, moisture content, soil density, loading conditions, and depth of foundation.

Analytical methods are detailed, consist of Terzaghi's theory, which assumes general shear failure and derives bearing capacity factors (N_c, N_q, N_γ) for strip, square, and circular foundations, and Meyerhof's empirical extension includes correction factors like shape factor, depth factor, and inclination factor. Experimental methods, like Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Plate Load Test (PLT), are checked for their site-specific accuracy in assessing soil resistance.

The analysis then turns to the Eurocode 7 framework, which introduces semi-empirical equations for both drained and undrained soil conditions. It also outlines the unique design approaches (DA1 involving dual verification, DA2 applying balanced load and resistance factors, and DA3 based on conservative soil assumptions) together with partial safety factors that help considering unpredictability.

A comparative analysis highlights the Advantages and disadvantages: analytical methods offer quick, cost-effective preliminary estimates but may be conservative in complex soils; experimental approaches provide reliable field data but are resource-intensive; Eurocode 7 ensures standardized, safe designs with built-in conservatism, particularly suitable for regulatory compliance in applications like wind turbine foundations on stable soils, where shallow mat designs are recommended under cyclic and overturning loads.

In conclusion, integrating these methods, supported by thorough site investigations, yields optimal, efficient designs. Recommendations emphasize conservative factors in variable conditions and suggest future research into computational modelling and dynamic loading effects.

Keywords Shallow foundations, bearing capacity, Terzaghi theory, Meyerhof theory, Eurocode 7, Comparison
Pages 54 pages

Contents

Figures

Equations

Tables

1 Introduction

Foundations represent a critical component of any structure. Positioned at the base of buildings or other constructions, their primary function is to transfer the forces from the superstructure (the portion visible above ground level) safely to the ground. In a simpler word, foundations ensure that structures remain stable and do not experience excessive settlement, tilting, or failure. (M. Das, 2019, p. 207)

In general, foundations are categorized into two main types according to their depth: shallow foundations and deep foundations. Shallow foundations are typically adopted when appropriate soil is located close to the ground surface, meaning that extensive excavation is unnecessary. This category includes:(M.Das, 2019, p. 207)

- Pad (spread) footings: These are relatively small concrete elements, usually square or rectangular in shape and they also can be circular. They are placed beneath individual columns to distribute the load safely onto the soil.
- Strip (continuous) footings: These are long foundations designed to provide support along the length of walls, which distribute the load evenly into the soil.
- Mat (raft) foundations: These extend over a large area of the ground and are designed to support several columns or walls together; They distribute loads across the entire foundation.

For a shallow foundation to perform effectively, two key conditions must be satisfied:(M.Das, 2019, p. 207)

1. Shear stability: The foundation must remain safe from shear failure, meaning the soil beneath should not collapse or yield under the applied loads.
2. Controlled settlement: While some settlement is unavoidable, extra movement can damage the structure. The acceptable level of settlement varies depending on the building type and its intended use.

The ultimate bearing capacity is a major concept in design of foundations. It represents the maximum force per unit area that the soil can take before experiencing shear failure. If the pressure from a structure exceeds this limit, the soil may collapse, potentially causing the building to settle extremely or become unstable.(M.Das, 2019, pp. 207 & 208)

This thesis explores several key aspects of shallow foundations. It examines the fundamental principles governing their behaviour, explains the concept of bearing capacity along with the numerous factors that influence it, and reviews different methods for calculating bearing capacity, with particular emphasis on the approach outlined in Eurocode 7. By the conclusion of this thesis, the aim is to offer a clear understanding of the behaviour of shallow foundations and the principles for their safe design.

2 Fundamental of foundations

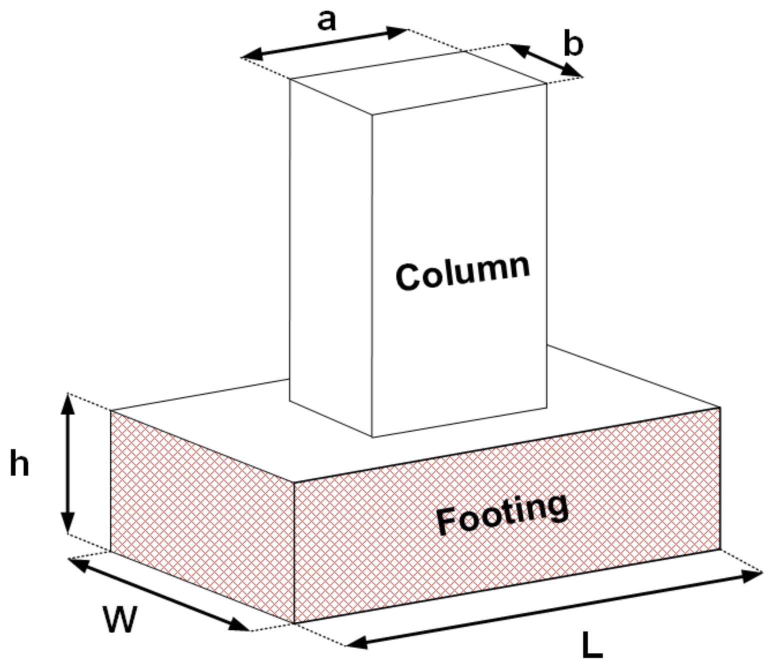
According to the book of principal of foundation engineering from M. Das “Shallow foundations are the structural elements that transfer the loads from the buildings or structures to the soil. These foundations distribute the load over a large area near the ground surface making sure that the soil can support the structure without an excessive failure or settlement”. (M. Das, 2019, p. 207)

2.1 Types of shallow foundations

Shallow foundations can be classified according to factors such as building design, soil conditions, load requirements, intended function, and shape. Some of the most common examples include:(Shree TMT, 2024)

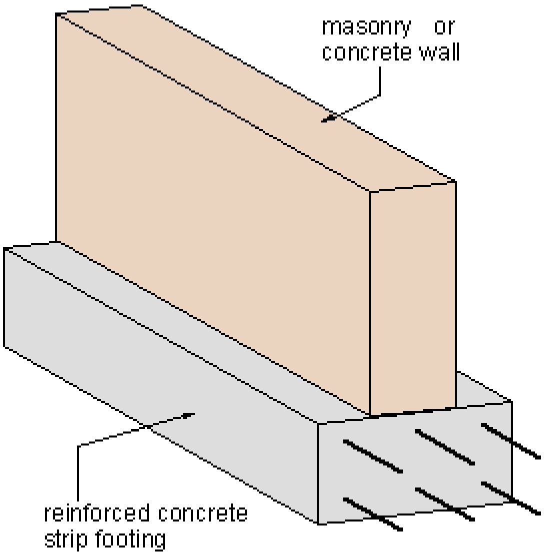
Pad footing (spread footing, isolated footing, or individual footing): These types of footings are typically square or rectangular concrete elements which are designed to support a single column or wall. They represent the simplest form of shallow foundation and are commonly used for individual columns in framed structures(Shree TMT, 2024).In the figure 1 below a pad footing is shown:

Figure 1. Pad footing(Pad Footing Analysis - Structural Engineering Design Centre)



Strip footing (Continuous footing or wall footing): These footings are long, continuous concrete strips that support a wall and are as long as the wall. They distribute the weight of the wall evenly across the soil and are typically used for load-bearing walls(Shree TMT, 2024). Figure 2 depicts a structure of a strip footing:

Figure 2. Strip footing(Strip Footing)

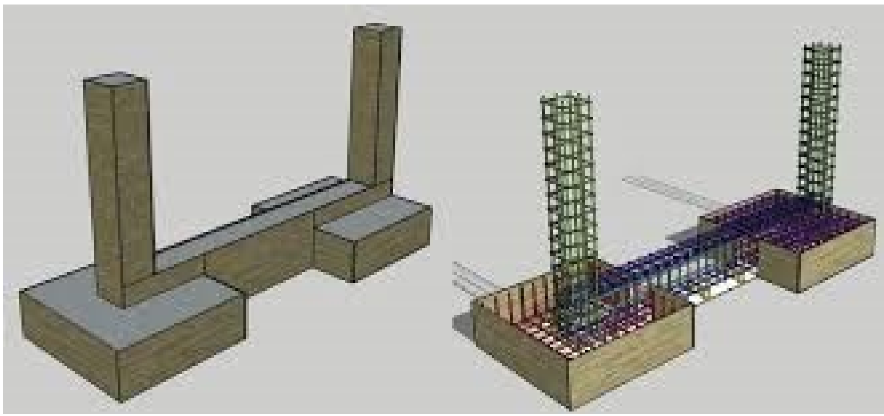


Combined footing: When columns are remarkably close to each other and separate footings are used, then they might overlap. In these situations, a combined footing is a proper option to use. It can be said that combined footing is a single larger footing that supports the several structural elements(Shree TMT, 2024). Figure 3 below shows a combined footing:

Figure 3. Combined footing(What Are Combined Footings | Gharpedia)

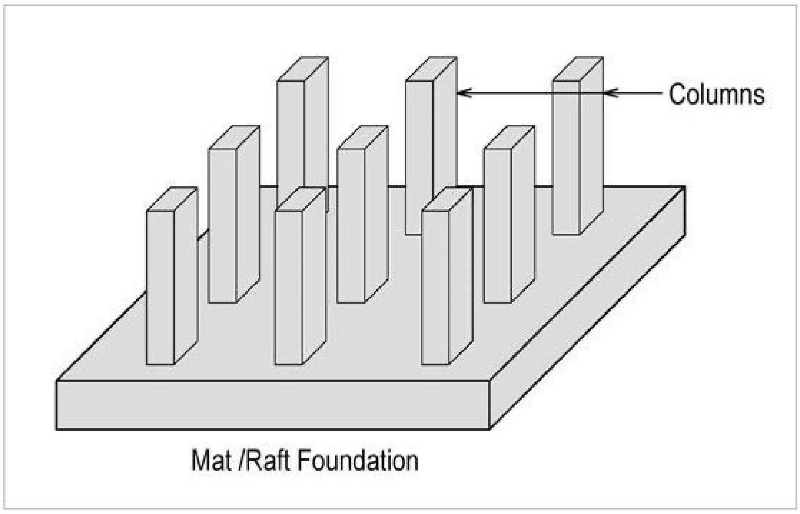
Cantilever footing (Strap footing): These L-shaped footings are in use when a wall is located next to a property line or an excavation. The cantilevered portion helps distribute the load further into the soil and away from the property line(Shree TMT, 2024): A strap footing is shown in the figure 4:

Figure 4. Strap footing(Prasad, 2022)



Mat foundation (Raft foundation): Used for structures on weak or uneven soil, this type of foundation consists of a thick concrete slab that spans the entire base of the building, distributing the load evenly over a large area. (Shree TMT, 2024).Figure 5 represents a general structure of a mat foundation:

Figure 5. Mat foundation(Laying a Firm Foundation: A Detailed Examination of Mat or Raft Systems in Construction – U-Property PH)



3 Bearing capacity of soils (general concept)

Soil bearing capacity is classified into two main types, ultimate bearing capacity and allowable bearing capacity.

Ultimate bearing capacity soil: The ultimate bearing capacity of soil refers to the maximum vertical pressure that can be applied to the ground before a shear failure happens in the supporting soil. Depending on the stiffness of the soil and the depth of foundation, this failure can take the form of general, local, or punching shear. Commonly, the ultimate bearing capacity expresses the maximum load the soil can withstand before destruction. However, this value alone is not used directly in foundation design, as it is also crucial to consider the soil's settlement under load, which can shock its ability to support a structure safely. (Lees, 2021)

Allowable bearing capacity of soil: The allowable bearing capacity of soil is the load that the soil can safely support without going under shear failure or enormous settlement. This is the value which is used in foundation design. Allowable bearing capacity value It is always lower than the ultimate bearing capacity value because it considers not only for the load that would cause shear failure but also for the soil’s settlement behaviour. (Lees, 2021)

According to M. Das in Principles of Foundation Engineering book “Considering a strip foundation with width of B resting on the surface of a dense sand or a cohesive soil as shown in the figure 6. when the load due to the superstructure applies to the footing constantly, the settlement increases. The fluctuation of the load per unit of area of the foundation (q) with the foundation settlement is also shown in figure 6. At a certain point when the load per unite of area equals q_u, a sudden failure in the soil which supports foundation will happen and the failure surface in the soil will extend to the ground surface. When such a sudden failure in the soil happens, it is called general shear failure”.(M.Das, 2019, p. 208)

It also explains that “If a foundation is placed on medium-compacted sand or clayey soil (Figure 6), an increase in load will result in greater settlement. In this case, the failure surface in the soil gradually extends outward from the foundation, as illustrated by the solid lines in Figure 6. In general, there are 3 types of shear failure in bearing capacity of the soil: general shear failure (Figure 6), Local shear failure (Figure 7) and punching shear failure (Figure 8).”(M.Das, 2019, p. 208)

Figure 6. General shear failure (M.Das, 2019, p. 208)

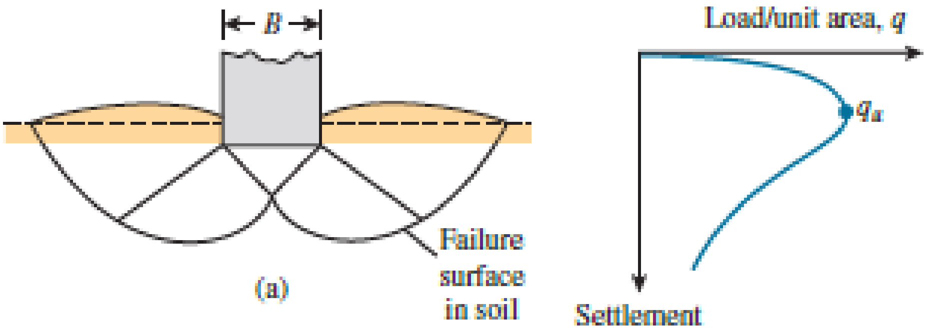


Figure 7. Local shear failure(M.Das, 2019, p. 208)

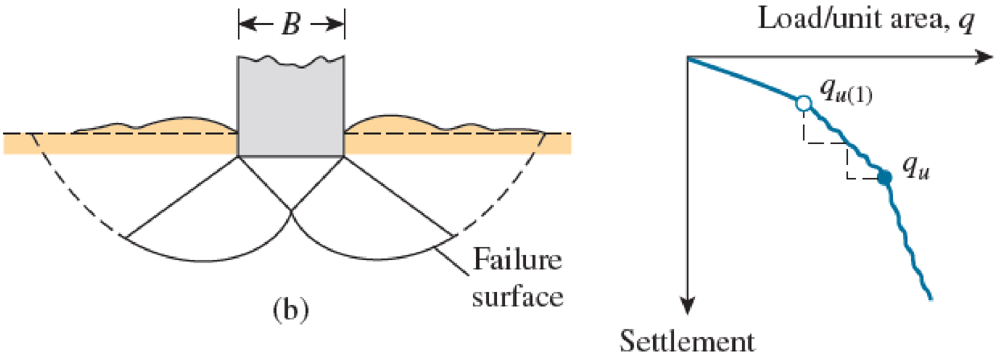
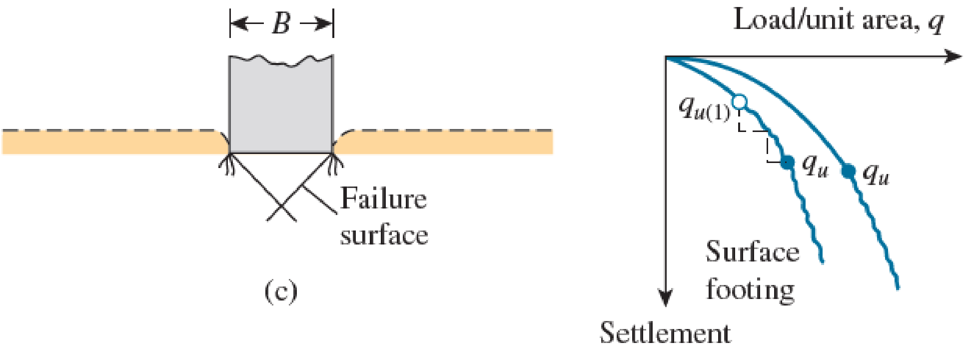


Figure 8. Punching shear failure(M.Das, 2019, p. 208)



The principal of foundation engineering book also explains what punching shear failure and local shear failure is. According to M. Das “the load per unit area on the foundation reaches $q_{u\,(1)}$, the foundation's movement will occur in sudden jerks. At this stage, significant movement is required for the failure surface in the soil to fully extend to the ground surface, as it is shown by the broken lines in the figures 7. The load per unit area at which this occurs is known as the ultimate bearing capacity (q_u). Beyond this point, any further increase in load results in a big rise in foundation settlement. The load per unit area $q_{u\,(1)}$ is referred to as the first failure load**.** It is important to note that in this type of failure, known as local shear failure, a peak value of q is not observed.” (M. Das, 2019, p. 208)

“When a foundation is placed on relatively loose soil, the load-settlement curve will resemble the one shown in Figure 8. In this scenario, the failure surface in the soil does not extend to the ground surface. Once the ultimate failure load (q_u) is reached, the load-settlement curve becomes steep and linear. This type of soil failure is known as punching shear failure.”(M.Das, 2019, p. 208)

3.1 Factors affecting bearing capacity

Several factors that affect the bearing capacity of shallow foundations. Some of these key factors are:

1. Type of soil:

   The bearing capacity of a foundation varies depending on the type of soil. Gravel and Sands are in category of coarse-grained soils which they have high bearing capacities because of the good drainage and particle uniting. They remain stable regardless of moisture changes. Moisture content significantly affects bearing capacity. For instance, dry clay is strong and boosts the soil’s bearing capacity, whereas wet clay is weaker due to reduced shear strength and increased plasticity. On the other hand, Silt has moderate strength but absorbs water easily, which can lead to instability under load and requires careful consideration in foundation design.(Truong, 2024)

2. Moisture content:

   The soil’s moisture content plays a crucial role in determining its bearing capacity. When the soil is dry it is stronger and more stable because its particles stay tightly together and allows it to support more load but when the soil is saturated it is weak, because water reduces compaction and increasing pressure, which can cause displacement or failure.(Truong, 2024)

3. Soil density and compaction:

   When soil is dense and well-compacted, it can support higher loads due to tightly packed and locked particles that resist deformation, whereas loose and poorly compacted soil has a lower bearing capacity because of larger gaps and weak particle cohesion, making it more prone to settlement under load.(Truong, 2024)

4. Load condition:

   Uniformly distributed loads are better supported by the soil because they spread the pressure equally across the foundation and reduces the risk of localized stress that could weaken the soil and cause instability. In opposite, concentrated point loads, such as those from columns or individual footings, create high stress over small areas, which can lower the soil’s bearing capacity and require careful assessment or reinforcement to prevent failure.(Truong, 2024)

5. Foundation depth:

   The depth of a foundation affects its bearing capacity. In soils with good strength near the ground surface, shallow foundations, such as strip or pad footings, are effective because they transfer loads directly to the supporting soil and making them a cost-efficient option for stable ground conditions.(Truong, 2024)

4 Methods for calculating bearing capacity

There are various methods for calculating bearing capacity of foundations such as basic methods, which they will be studied in this thesis, and advanced methods like numerical analysis and machine learning models. There are three basic ways for calculating bearing capacity: Analytical methods (Terzaghi and Meyerhof theories, Experimental approaches, and Eurocode 7 approach). In this thesis all three methods are going to be analysed and compared.

4.1 Analytical method (Terzaghi and Meyerhof methods)

Analytical methods involve formulas and equations extracted from soil mechanics, soil properties, and soil behaviour under foundations. By using these methods, engineers can calculate the bearing capacity of soil that is, the maximum load the soil can safely support before any failure occurs. Analytical methods rely on mathematical equations and principles of mechanics rather than computer simulations or experimental testing, which is the reason that they are referred to as “analytical.” Among the most well-known approaches are Terzaghi’s and Meyerhof’s bearing capacity equations which will be discussed in this thesis.

4.1.1 Terzaghi bearing capacity theory

To learn and analyse the Therzaghi’s bearing capacity theory, The Principal of foundation engineering from M. Das is used as the reference; the next paragraphs has been directly taken from his book.

“Terzaghi is one of the most functional methods of calculating ultimate bearing capacity of soil. Karl Therzaghi in1943 provided an analytical approach determined the maximum load that soil can support before failure. According to Terzaghi, a foundation is considered shallow if its depth (D_f) is less than or equal to its width (B). However, later research suggests that foundations with depths up to three to four times their width may also be classified as shallow.”(M.Das, 2019, p. 212)

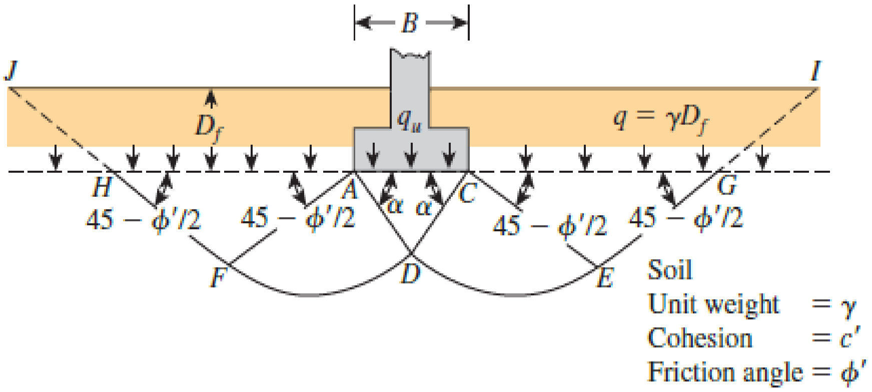
“Terzaghi proposed that for a continuous (strip) foundation, where the width-to-length ratio is exceedingly small ($\frac{D_f}{B}$). the failure surface in the soil at ultimate load resembles the pattern shown in Figure 9. This represents a general shear failure, as illustrated in Figure 6. Since foundations are typically placed on well-compacted ground, assuming general shear failure is reasonable.”(M.Das, 2019, p. 212)

“The soil above the base of the foundation can be replaced with an equivalent surcharge, expressed as $q = \gamma \times D_f$, where γ is the unit weight of the overlying soil.” (M. Das, 2019, p. 212)

The failure zone beneath the foundation is divided into three main sections (Figure 9).(M.Das, 2019, p. 212)

1) Triangular Zone (ACD): Directly beneath the foundation.
2) Radial Shear Zones (ADF and CDE**):** Defined by logarithmic spiral curves (DE and DF).
3) Rankine Passive Zones (AFH and CEG): Two triangular regions influenced by passive earth pressure.

Figure 9. Failure zones in Terzaghi’s theory. Bearing capacity in soil under a rough rigid strip foundation (M.Das, 2019, p. 212)



“The angles CAD and ACD are assumed to be equal to the soil's friction angle (ϕ′). Since the soil above the foundation base is replaced by an equivalent planar distributed load (q), the shear resistance along the failure surfaces GI and HJ is disregarded.”(M.Das, 2019, p. 212)

“The ultimate bearing capacity (q_u) of the foundation can be determined by analysing the equilibrium of the triangular wedge ACD shown in Figure 9, which is maximized in Figure 10.

When a load per unit area (q_u) is applied, and general shear failure occurs, a passive force (P_p) acts on both faces of the soil wedge ACD.”(M.Das, 2019, p. 212)

“This can be understood by visualizing AD and CD as retaining walls pushing the adjacent soil masses ADFH and CDEG, causing passive failure. The passive force P_p is inclined at an angle δ´ (the wall friction angle) to the perpendicular drawn to AD and CD. Since soil is present on both sides of these surfaces, δ´ is assumed equal to the soil friction angle (ϕ′).”(M.Das, 2019, p. 212)

“Given that AD and CD are inclined at an angle ϕ´ to the horizontal, the passive force (P_p) acts vertically. For a unit length of the foundation, equilibrium equations can be formulated accordingly. Considering a unit length of the foundation, according to equilibrium situation we have:”(M.Das, 2019, p. 212)

Equation 1. Equation based on equilibrium condition

$$(\mathrm{q_u})(2\mathrm{b})(1) = -\mathrm{W} + 2\mathrm{C}\sin\emptyset' + 2\mathrm{P_p}$$

Where:

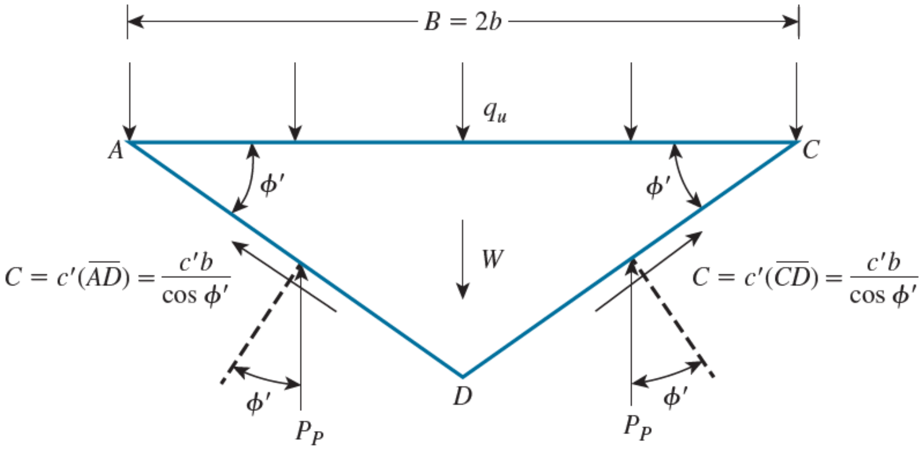
$$b = \frac{B}{2}$$

$$W = \text{weight of soil wedge ACD} = \gamma b^2 \tan \emptyset'$$

$$C = \frac{c'b}{\cos \emptyset'}$$

C is the cohesive force acting along each face, AD and CD, which is equal to the unit cohesion times the length of each face.

Figure 10. Derivation of Eq.1 (M.Das, 2019, p. 213)



Thus,

Equation 2.Founded equation from triangular zone

$$2bq_u = 2P_p + 2bc' \tan \emptyset' - \gamma b^2 \tan \emptyset'$$

Or

Equation 3. Founded equation from triangular zone

$$q_u = \frac{P_p}{b} + c' \tan \emptyset' - \frac{\gamma b}{2} \tan \emptyset'$$

“The passive force P_p in Eq. (1) is the sum of the contribution of the weight of soil γ , cohesion c´, and surcharge q. Figure 11 shows the distribution of passive pressure from each of these components on the wedge face CD. Thus, we can write:”(M.Das, 2019, p. 213)

Equation 4. Equation founded by triangular zone and substitution equation 1 terms inside

$$P_p = \frac{1}{2}\gamma(b \tan \emptyset')^2 K_\gamma + c'(b \tan \emptyset')K_c + q(b \tan \emptyset')K_q$$

Where K_γ , K_c, and K_q are earth pressure coefficients that are functions of the soil friction angle, ϕ'. Combining Equations (3) and (4), we obtain:

Equation 5. Therzaghi’s original bearing capacity equation

$$q_u = c'N_c + qN_q + \frac{1}{2}\gamma B N_\gamma$$

Where:

Equation 6. First bearing capacity factor in Terzaghi’s theory

$$N_c = \tan\emptyset'(K_c + 1)$$

Equation 7. Second bearing capacity factor in Terzaghi’s theory

$$N_q = K_q \tan \emptyset'$$

Equation 8. Third bearing capacity factor in Terzaghi’s theory

$$N_\gamma = \frac{1}{2}\tan \emptyset' (K_\gamma \tan \emptyset' - 1)$$

where Nc, Nq, and Nγ are called bearing capacity factors.

“The bearing capacity factors Nc, Nq, and Nγ are, respectively, the contributions of cohesion, surcharge, and unit weight of soil to the ultimate load-bearing capacity. It is extremely tedious to evaluate Kc, Kq, and Kγ. For this reason, Terzaghi used an approximate method to determine the ultimate bearing capacity, q_u. The principles of this approximation are given here:”(M.Das, 2019, p. 213)

1. If $\gamma = 0$ (weightless soil) and $C = 0$, then

Equation 9. Bearing capacity equation for weightless soil

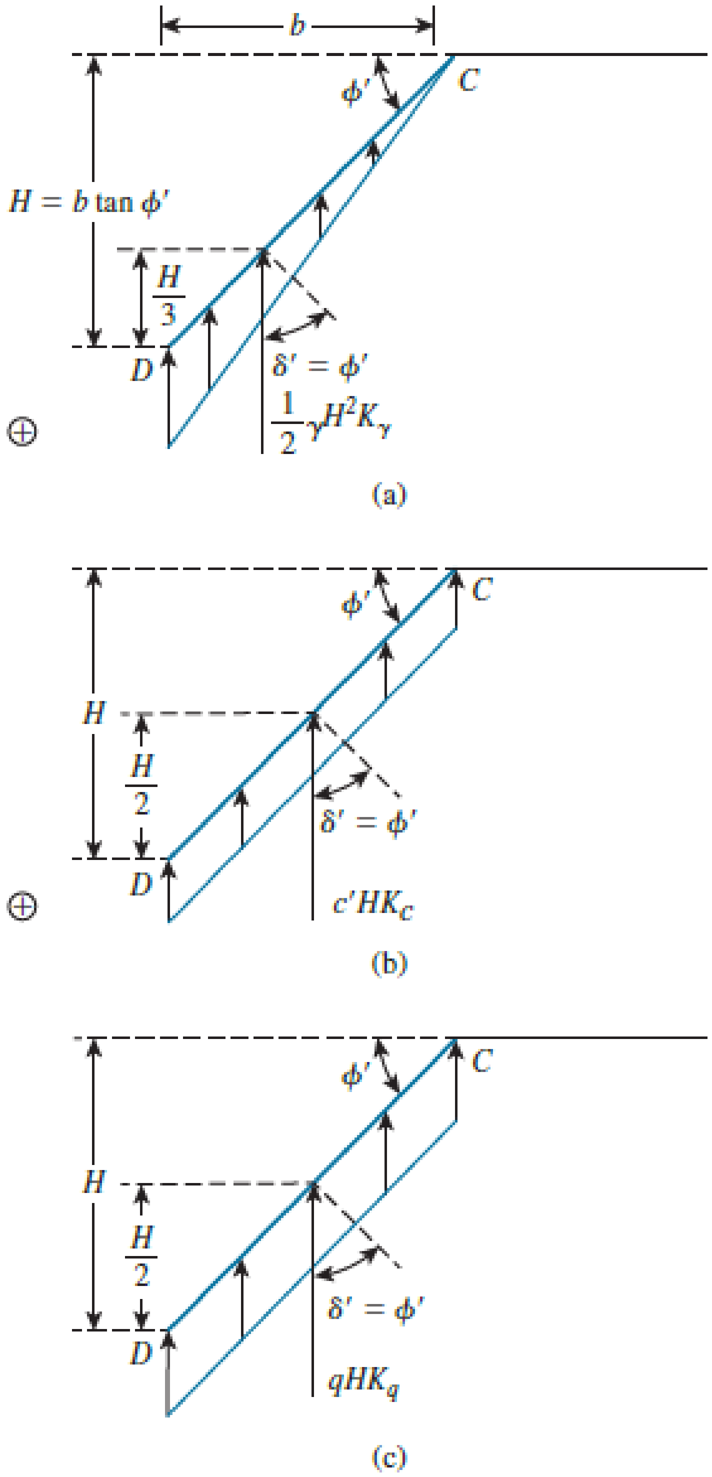
$$q_u = q_q = qN_q$$

Where

Equation 10.Second bearing capacity factor in Terzaghi's theory for weightless soil

$$N_q = \frac{e^{2(\frac{3\pi}{4}-\frac{\phi'}{2})\tan\phi'}}{2\cos(45+\frac{\phi'}{2})^2}$$

Figure 11. Passive force distribution on the wedge face CD shown in Figure 10: (a) contribution of soil weight γ; (b) contribution of cohesion c´; (c) contribution of surcharge q (M.Das, 2019, p. 214)



Note: $H = b \tan \phi'$

$$P_P = \frac{1}{2}\gamma H^2 K_\gamma + c' H K_c + q H K_q$$

2. If $\gamma = 0$ (that is, weightless soil) and $q = 0$, then

Equation 11. Bearing capacity equation for weightless soil

$$q_u = q_c = c'N_c$$

Where

Equation 12. First bearing capacity factor in Terzaghi's theory for weightless soil

$$N_c = \cot \phi' \left[\frac{e^{2\left(\frac{3\pi}{4} - \frac{\phi'}{2}\right)\tan \phi'}}{2\cos\left(45 + \frac{\phi'}{2}\right)^2} - 1 \right] = \cot \phi' \,(N_q - 1)$$

1. If $c' = 0$ and surcharge $q = 0$ (that is, $D_f = 0$), then

Equation 13. Terzaghi's equation when foundation depth is equal to zero

$$q_u = q_\gamma = \frac{1}{2}\gamma B N_\gamma$$

“The magnitude of N_γ for various values of ϕ' is determined by trial and error. The variations of the bearing capacity factors defined by Equations (12), (10), and (8) are given in Table1.”(M.Das, 2019, p. 214)

Table 1. Terzaghi’s Bearing Capacity Factors equations (12), (10), and (8).(M.Das, 2019, p. 215)

φ'	**N_c**	**N_q**	**N γ'**	**φ'**	**N_c**	**N_q**	**N γ'**
0	5.70	1.00	0.00	26	27.09	14.21	9.84
1	6.00	1.10	0.01	27	29.24	15.90	11.60
2	6.30	1.22	0.04	28	31.61	17.81	13.70
3	6.62	1.35	0.06	29	34.24	19.98	16.18
4	6.97	1.49	0.10	30	37.16	22.46	19.13
5	7.34	1.64	0.14	31	40.41	25.28	22.65
6	7.73	1.81	0.20	32	44.04	28.52	26.87
7	8.15	2.00	0.27	33	48.09	32.23	31.94
8	8.60	2.21	0.35	34	52.64	36.50	38.04
9	9.09	2.44	0.44	35	57.75	41.44	45.41
10	9.61	2.69	0.56	36	63.53	47.16	54.36
11	10.16	2.98	0.69	37	70.01	53.80	65.27
12	10.76	3.29	0.85	38	77.50	61.55	78.61
13	11.41	3.63	1.04	39	85.97	70.61	95.03
14	12.11	4.02	1.26	40	95.66	81.27	115.31
15	12.86	4.45	1.52	41	106.81	93.85	140.51
16	13.68	4.92	1.82	42	119.67	108.75	171.99
17	14.60	5.45	2.18	43	134.58	126.50	211.56
18	15.12	6.04	2.59	44	151.95	147.74	261.60
19	16.56	6.70	3.07	45	172.28	173.28	325.34
20	17.69	7.44	3.64	46	196.22	204.19	407.11
21	18.92	8.26	4.31	47	224.55	241.80	512.84
22	20.27	9.19	5.09	48	258.28	287.85	650.67
23	21.75	10.23	6.00	49	298.71	344.63	831.99
24	23.36	11.40	7.08	50	347.50	415.14	1072.80
25	25.13	12.72	8.34	-	-	-	-

To estimate the ultimate bearing capacity of *square* and *circular foundations*, Equation (5) may be respectively modified to:(M.Das, 2019, p. 215)

Equation 14. Terzaghi’s bearing capacity equation for square foundation

$$q_u = 1.3c'N_c + qN_q + 0.4\gamma BN_\gamma$$

And

Equation 15. Terzaghi’s bearing capacity equation for circular foundation

$$q_u = 1.3c'N_c + qN_q + 0.3\gamma BN_\gamma$$

“In Eq. (14), B equals the dimension of each side of the foundation; in Eq. (15), B equals the diameter of the foundation. Terzaghi’s bearing capacity equation [Eq. (5)] and the bearing capacity factors surcharge, and the soil weight that contribute to the ultimate bearing capacity, the equation has been modified to account for the effects of the foundation shape ($\frac{B}{L}$), foundation depth (D_f), and inclination in the applied load. Terzaghi’s original bearing capacity equation [Eq. (5)] still provides good estimates of the ultimate bearing capacity, but these estimates can be conservative. Have been modified.”(M.Das, 2019, p. 215)

4.1.2 Meyerhof bearing capacity theory

In 1963, Meyerhof introduced a method for calculating the bearing capacity of shallow foundations that provided an alternative to earlier approaches like Terzaghi’s. Unlike Terzaghi’s method, Meyerhof’s approach is more empirical, it relies on real-world observations and practical experience from field studies. He developed simplified equations to estimate ultimate bearing capacity and used correction factors to improve accuracy by considering different practical conditions: (Soil Bearing Capacity, 2025)

These correction factors are:

Shape factor: This factor modifies the bearing capacity based on the foundation’s shape. Because different shapes (circular or rectangular footings) affect how loads are distributed into the soil, The shape factor satisfies these differences.(Soil Bearing Capacity, 2025)

Depth factor: This factor considers the foundation’s depth. As the foundation is placed deeper, the surrounding soil provides greater resistance to shear, which increases the bearing capacity.(Soil Bearing Capacity, 2025)

Inclination factor: This factor considers for both the angle of the applied load and the angle of the slop that the footing is placed on. Angular (non-vertical) loads can reduce the ability of soil to support the foundation.(Soil Bearing Capacity, 2025)

Meyerhof’s ultimate bearing capacity equation is:

Equation 16. Meyerhof’s ultimate bearing capacity equation

$$q_u = s_c N_c d_c i_c c' + s_q N_q d_q i_q \gamma D + \frac{1}{2}\gamma B s_\gamma N_\gamma d_\gamma i_\gamma$$

Where:

C´➔ cohesion of the drained soil (kPa)

γ➔ Unit weight of the soil (kN/m^3)

D➔ Depth of the footing below the ground level (m)

B➔ Width of the footing (m)

N_c, N_q and N_γ➔ Bearing capacity factors

S_c, S_q and S_γ➔ Shape factors

d_c, d_q and d_γ➔ Depth factors

i_c, i_q and i_γ➔ Inclination factors

The bearing capacity factors, which correspond to soil cohesion, overburden pressure, and the unit weight of the soil, are defined as follows:(Soil Bearing Capacity, 2025)

Equation 17. First bearing capacity factor in Meyerhof's theory

$$N_q = \frac{1+\sin \emptyset'}{1-\sin \emptyset'} e^{\pi \tan \emptyset'}$$

Equation 18. Second bearing capacity factor in Meyerhof's theory

$$N_c = (N_q - 1) \cot \emptyset'$$

Equation 19. Third bearing capacity factor in Meyerhof's theory

$$N_\gamma = \left(N_q - 1\right) \tan\left(1.4\emptyset'\right)$$

The shape factor equations are:

Equation 20. First shape factor equation in Meyerhof’s theory

$$\mathrm{S_c} = 1 + 0.2\frac{1 + \sin(\emptyset')}{1 - \sin(\emptyset')}\left(\frac{\mathrm{B}}{\mathrm{L}}\right)$$

Equation 21. Second and Third shape factors equation in Meyerhof’s theory

$$\mathrm{S_q} = \mathrm{S_\gamma} = 1 + 0.1\frac{1 + \sin(\emptyset')}{1 - \sin(\emptyset')}(\frac{\mathrm{B}}{\mathrm{L}})$$

The equations regarded to depth factor are:

Equation 22. First depth factor equation in Meyerhof’s theory

$$\mathrm{d_c} = 1 + 0.2\sqrt{\frac{1 + \sin(\emptyset')}{1 - \sin\,(\emptyset')}}(\frac{\mathrm{D}}{\mathrm{B}})$$

Equation 23. Second and third depth factors equation in Meyerhof’s theory

$$\mathrm{d_q} = \mathrm{d_\gamma} = 1 + 0.1\sqrt{\frac{1 + \sin\emptyset'}{1 - \sin\emptyset'}}(\frac{\mathrm{D}}{\mathrm{B}})$$

The equations which represent inclination factor are:

Equation 24. First and second inclination factors in Meyerhof’s theory

$$\mathrm{i_c} = \mathrm{i_q} = \left(1 - \frac{\alpha}{90^\circ}\right)^2$$

Equation 25. Third inclination factors in Meyerhof’s theory

$$\mathrm{i_\gamma} = \left(1 - \frac{\alpha}{\emptyset'}\right)^2$$

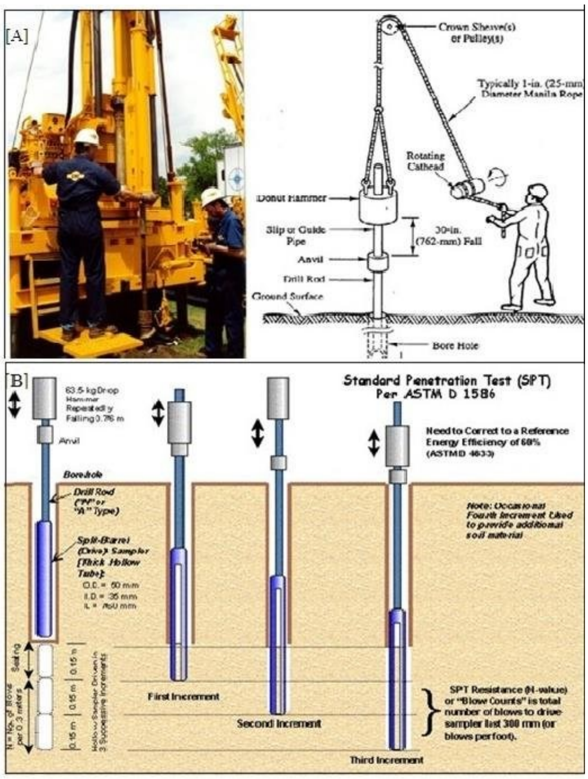
4.2 Experimental approach

In addition to relying completely on analytical formulas, experimental methods which are the result of result of many years of practical experience in geotechnical engineering can also be employed. The most common tests to determine soil bearing capacity in experimental approaches are Standard Penetration Test (SPT), Cone Penetration Test (CPT) and Plate Load Test (PLT).

The Standard Penetration Test (SPT) is one of the most Common methods for analysing the bearing capacity of both fine- and coarse-grained soils. However, its results are less reliable for clay and gravel. The test includes driving a split-barrel sampler into the bottom of a borehole by using repeated hammer blows. The N-value is a parameter which shows the soil's strength, and it is determined based on the number of blows which is required for the sampler to penetrate a specified depth. The higher the magnitude of N-value is, It shows that the ground is stronger(Lees, 2021). Figure 12 and figure 13 shows how STP is done

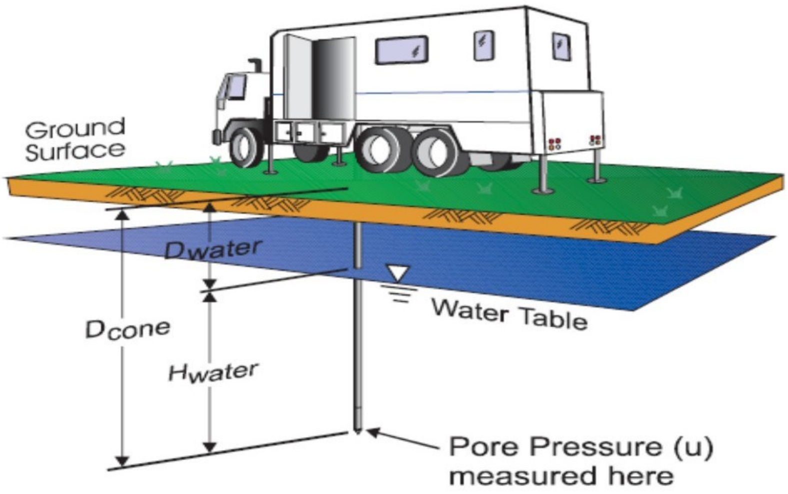
Figure 12. Standard penetration test (SPT) (Cuffaro, 2024)

Figure 13. Standard penetration test tool(Fauzi, 2016)



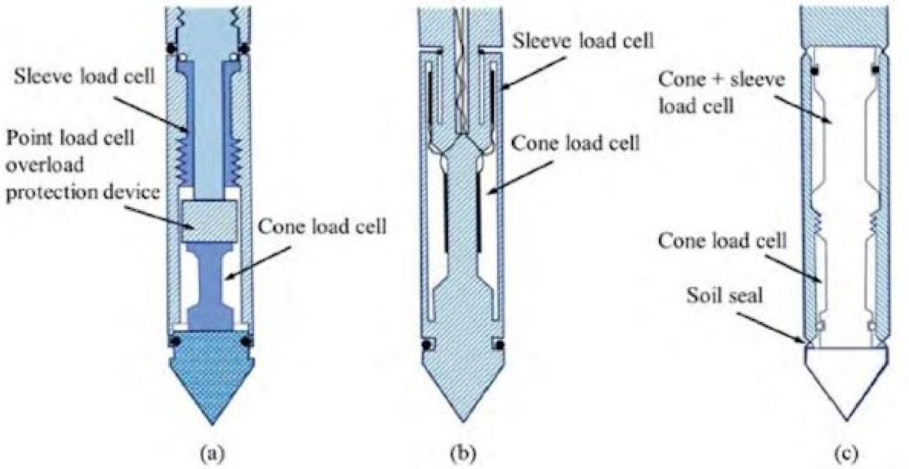
The Cone Penetration Test (CPT) is a dynamic method used to measure the soil's resistance to penetration. In this test, a cone-shaped probe is pushed into the ground at a constant rate while the resistance is continuously recorded. The Cone Penetration offers a detailed profile of the soil's properties and resistance. This testing metho, provides more comprehensive information than some other tests.(Lees, 2021). In the figure 14 and 15 the idea of CPT is shown.

Figure 14. Cone penetration test (CPT) (Tomiša, 2019)



t

Figure 15.Cone penetration test tool(*Cone Penetration Testing (CPT)*)



The Plate Load Test determines the bearing capacity and strength of soil by applying continuously increasing loads through a circular steel plate. As the load is applied, the resulting settlement is measured, and the soil's behaviour under pressure is observed. This method is especially suitable for coarse-grained soils. (Lees, 2019)

A Plate Bearing Test is usually placed at the foundation level, either on the ground surface or in a shallow pit below a working platform. In this test, a circular steel plate is placed on the soil, and the load is constantly increased until the plate begins to settle quickly. This method offers several advantages for checking soil bearing capacity. Some of the main benefits are: (Lees, 2019)

- Plate bearing tests are quick and straightforward to realize.
- They can be done directly on-site.
- This method is suitable for different soil types.
- The tests show accurate and reliable results.
- This method is time-efficient and cost-efficient.
- The equipment is easy and simple to set up.

In plate load tests, plates with diameters of 0.3 m or 0.6 m are commonly used. The depth of soil affected by the test, which is called bulb, is twice the plate's diameter, it means a 0.3 m plate tests is used for depth of 0.6m. Therefore, the size of the plate influences the test results, this means that larger plates probe goes deeper into the ground, where the soil properties may be different. Deeper soils at greater depths are often weaker than the compacted soil near the surface and that can result in a lower measured bearing capacity compared to tests that smaller plates are used. Figure 16 depicts plate load test in construction field. (Lees, 2019)

Figure 16.Plate load test(Plate Load Testing | Plate Bearing Test)

5 Eurocode 7 approach to bearing capacity

According to annex D of EN 1997-1 (Eurocode 7: Geotechnical Design – Part 1: General Rules), Eurocode7 provides a simplified method for verifying the bearing resistance of spread foundations. This method is intended to be used under certain conditions where the ground properties and loading conditions meet predefined criteria.

“Approximate equations for the design vertical bearing resistance, derived from plasticity theory and experimental results, may be used. Allowance should be made for the effects of the following:”(*Eurocode 7: Geotechnical Design - Part 1: General Rules*, 2004, p. 156)

- The strength of the ground, represented by the design values of C_u
- C´ and ϕ’
- Eccentricity and inclination of design loads
- The shape, depth, and inclination of the foundation
- The inclination of the ground surface
- Ground water pressures and hydraulic gradients
- The variability of the ground, especially layering

5.1 Undrained conditions

The design bearing resistance may be calculated from:(Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 157)

Equation 26. Eurocode 7 bearing capacity equation for undrained condition

$$R/_{A'} = (\pi + 2)c_u b_c S_c i_c + q$$

With the dimensionless factors for:

The inclination of the foundation base:

Equation 27. Equation of inclination factor of the foundation base for undrained conditions

$$b_c = 1 - 2\alpha/(\pi + 2)$$

The shape of the foundation:

$S_c = 1 + 0{,}2\,(B'/L')$, for a rectangular shape.

S_c = 1.2, for a square or circular shape.

The inclination of the load, caused by a horizontal load H:

Equation 28. Equation of inclination factor caused by horizontal load

$$i_c = \frac{1}{2}\left(1 + \sqrt{1 - \frac{H}{A' * C_u}}\right)$$

Which $H \leq A' * C_u$

5.2 Drained conditions

The design bearing resistance may be calculated from:(Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 157)

Equation 29. Eurocode 7 bearing capacity equation for drained condition

$$R/_{A'} = C'N_c b_c s_c i_c + q'\,N_q b_q s_q i_q + 0{,}5\,\gamma' B\,' N_\gamma\, b_\gamma s_\gamma i_\gamma$$

The design values for dimensionless factors are:

The bearing resistance:

Equation 30. First bearing capacity factor equation in Eurocode 7 approach

$$N_q = e^{\pi tan\varphi\prime} tan^2(45 + \frac{\varphi}{2})$$

Equation 31. Second bearing capacity factor equation in Eurocode 7 approach

$$N_c \ = \ (N_q - \ 1) \, cot \, \phi'$$

Equation 32. Third bearing capacity factor equation in Eurocode 7 approach

$$N\gamma \ = \ 2 \ (Nq - \ 1) \ tan \ \phi', where \ \delta \ \geq \ \phi'/2 \ (rough \ base)$$

The inclination of the foundation base:

Equation 33. First equation of inclination factor of the foundation base for drained conditions

$$b_c \ = \ b_q \ - \ (1 \ - \ b_q) \ / \ (N_c tan \ \phi' \ )$$

Equation 34. Second and third equation of inclination factor of the foundation base for drained conditions

$$b_q = b_\gamma \ = \ (1 - \alpha . \tan \varphi')^2$$

The shape of foundation:

Equation 35. First shape factor equation for rectangular footings

$$Sq = 1 + (B' / L')\, sin\, \phi'$$

Equation 36. First shape factor equation for circular footings

$$S_q = 1 + sin\, \phi'$$

Equation 37. second shape factor equation for rectangular footings

$$S_\gamma = 1 - 0{,}3\, (B'/L')$$

Equation 38. First shape factor equation for circular footings

$$S_\gamma = 0.7$$

Equation 39. Third shape factor equation for both rectangular and circular footings

$$S_c = (S_q \cdot N_q - 1)/(N_q - 1)$$

The inclination of the load, caused by a horizontal load *H*:

Equation 40. First inclination factor equation caused by horizontal load

$$i_c = i_q - (1 - i_q) / (N_c . \tan \phi')$$

Equation 41. Second inclination factor equation caused by horizontal load

$$i_q = [1 - H/(V + A'c' \cot \phi')]m$$

Equation 42. Third inclination factor equation caused by horizontal load

$$i_\gamma = [1 - H/(V + A'c' \cot \phi')]m + 1$$

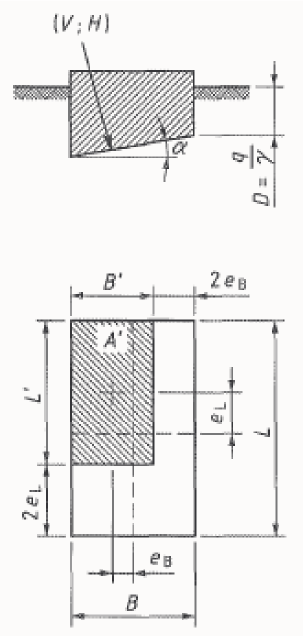
Where:

When H acts in the direction of B´:

Equation 43. First eccentricity checks equation

$$m = m_B = \left[\frac{2 + \left({}^{B'}/_{L'}\right)}{1 + \left({}^{L'}/_{B'}\right)}\right]$$

Figure 17. Eccentricity and load inclination (Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 158)



5.3 Design approaches (DA1, DA2, DA3)

The discussion of design approaches in this thesis is based on Designers Guide to Eurocode 7: Geotechnical Design, which has been used as a known reference. The following paragraphs are directly cited from this source.

5.3.1 Design Approach 1 (DA1)

"Design Approach 1 (DA1) has clarified the safety of structures by applying two different sets of partial factors that ensures the ultimate limit states (ULS). It can be considered as a double-check, one set of factors highlights the applied loads, while the other set focuses on the strength of the ground." (Frank & Kavvadas, 2004, p. 75)

"Combination 1 (A1 + M1 + R1): This uses higher factors on actions (loads) but keeps ground strength unchanged. Recommended factors include $\gamma_{\mathrm{G}} = 1.35$ for permanent loads, $\gamma_{\mathrm{Q}} = 1.5$ for variable loads, and $\gamma_{\mathrm{c}'} = \gamma_{\varphi'} = \gamma_{\mathrm{cu}} = 1$ for ground strength (Table A.3, A.4, A.5 of EN1997-1 Annex A). It ensures safety against unexpected high loads. For piles and anchorages, resistance factors **(**$\gamma_R > 1$) are applied directly to measured or calculated resistances."(Frank & Kavvadas, 2004, p. 75)

"Combination 2 (A2 + M2 + R1): This uses lower factors on loads ($\gamma_{\mathrm{G}} = 1$, $\gamma_{\mathrm{Q}} = 1.3$) but reduces ground strength with factors like and $\gamma_{\mathrm{c}'} = \gamma_{\varphi'} = 1.25$, $\gamma_{\mathrm{cu}} = 1.4$ (Table A.4). It ensures safety against weaker-expected ground. Typically, Combination 2 governs geotechnical sizing (e.g., foundation size), while Combination 1 checks structural strength."(Frank & Kavvadas, 2004, p. 75)

5.3.2 Design Approach 2 (DA2)

"Design Approach 2 (DA2) applies a single set of partial factors (A1 + M1 + R2) to either the actions or their effects. This design approaches focuses on factoring the soil resistance rather than the ground strength. This clear approach balances the level of conservatism between loads and resistance."(Frank & Kavvadas, 2004, pp. 76 & 77)

According to Finnish national annex 2.4.7.3.4.1(1)P," note 1**:** Design Approach 2 can be applied in two ways, denoted as DA2 and DA2*. In DA2, the actions are factored at their source and the design calculation is performed using factored values of actions. In DA2*, the design calculation is performed using characteristic values of actions, and partial safety factors are applied only at the end of the calculation in verifying the ultimate limit state condition. When using the design approach DA2*, special attention shall be given to the verification of the stability of a foundation structure."(*Finnish National Annex, Design of Foundations, Instructions*, n.d., p. 28)

"Factors are applied to actions ($\gamma_G = 1$, $\gamma_Q = 1.3$) and keep ground strength unchanged ($\gamma_{c'} = \gamma_{\varphi'} = \gamma_{cu} = 1$) (Table A.3, A.4). Resistance is reduced with factors like $\gamma_{Rv} = 1.4$ for bearing resistance (Table A.5). There are two variants:

DA2, Factors are applied to actions at the source (e.g., multiplying loads directly).

DA2*, Factors are applied to the effects of actions (e.g., moments or forces which are calculated from loads in load combinations)." (Frank & Kavvadas, 2004, pp. 76 & 77)

5.3.3 Design approach 3 (DA3)

"Design Approach 3 (DA3) is the most conservative method. In this method, Loads are higher (for example, 1.35 for self-weight of the building and 1.0 for soil pressure), while the soil strength is reduced by dividing it by factors like 1.25 or 1.4. Although the resistance is not reduced further, it will be assumed that weaker soil already results in a very safe design. DA3 is typically used when soil reliability is uncertain, for instance in soft clay or difficult ground conditions. In practice, Design approach 3 often leads to larger foundations because it assumes a worst-case scenario for the soil."(Frank & Kavvadas, 2004, pp. 77 & 78)

Table 2.Table A.1 partial factors on actions (Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 128)

Action	Symbol	Value
Permanent unfavourable	$\gamma_{G.dst}$	1.1
Permanent favourable	$\gamma_{G.stb}$	0.9
Variable unfavourable	$\gamma_{Q.dst}$	1.5
Variable favourable	$\gamma_{Q,stb}$	0

Table 3.Table A.2 Partial factors for soil parameters (γM)(Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 129)

Soil parameter	Symbol	Value
Angel of shearing resistance*	ϕ'	1.25
Effective cohesion	C'	1.25
Undrained shear strength	C_u	1.4
Unconfined strength	Q_u	1.4
Weight density	γ	1
* This factor is applied to tan ϕ		

Table 4.Table A.3 - Partial factors on actions (γF) or the effects of actions (γE)(Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 130)

Action		Symbol	Set	
			A1	A2
Permanent	Unfavourable	γ_G	1.35	1
	Favourable		1.35	1
Variable	Unfavourable	γ_Q	1.5	1.3
	Favourable		0	0

Table 5.Table A.4 - Partial factors for soil parameters(γM)(Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 130)

Soil parameter	Symbol	Set	
		M1	M2
Angel of shearing resistance*	ϕ'	1	1.25
Effective cohesion	C'	1	1.25
Undrained shear strength	C_u	1	1.4
Unconfined strength	Q_u	1	1.4
Weight density	γ	1	1
* This factor is applied to tan ϕ			

Table 6.Table A.5 Partial resistance factors (γ R) for spread foundations (Eurocode 7: Geotechnical Design - Part 1: General Rules, 2004, p. 131)

Resistances	Symbol	Set		
		R1	R2	R3
Bearing	$\gamma_{R,v}$	1	1.4	1
Sliding	$\gamma_{R,h}$	1	1.1	1

5.3.4 Differences between design approaches:

Design approach 1 (DA1): This approach is very comprehensive and easy to understand, and it uses two separate checks for both high loads and weak soil conditions. It is typically applied in complicated designs like pile foundations or retaining walls design.

Design approach 2 (DA2): This approach is simpler; it balances load and resistance factors, which makes it applicable for simple and straightforward designs like spread foundations.

Design approach 3 (DA3): This is the most conservative approach which emphases weak soil assumptions. This design approach is used when ground conditions are uncertain, like checking the overall stability.

6 Comparison between analytical methods, experimental approaches, and Eurocode7:

In this section which is the final goal and purpose of this thesis, all the methods which discussed in this research (Analytical approaches, Experimental approaches, and Eurocode 7 approach) will be compared together detailed. Thsis comparison consists of several aspects such as basis, advantages, limitations, applications, reliability, and accuracy.

Analytical approaches such as Terzaghi and Meyerhof theories are based on soil properties and factors including shape factor, depth factor, and inclination factor. Terzaghi’s method assumes general shear failure, while Meyerhof extends this with correction factors to account for practical variability. These methods are quick, cost-effective, easy to understand, and flexible for different soil types which makes them ideal for basic designs. However, their assumptions such as Terzaghi ignoring shear above the base can be conservative, and they are less accurate for complex soils. Analytical approaches require reliable soil parameters and are typically applied in general designs on uniform soils, for example, Terzaghi’s method for dense sands or Meyerhof’s method when dealing with inclined loads. In terms of accuracy, they are moderate; empirical adjustments like Meyerhof’s improve results, but they may overestimate bearing capacity in layered soils.

Experimental methods discussed in this thesis are based on direct field measurements of soil resistance. For example, the Standard Penetration Test calculates N-value, the Cone Penetration Test records cone resistance, and the Plate Load Test determines settlement under applied loads. These approaches provide efficient information that shows actual site conditions and are widely used in geotechnical investigations. The Cone Penetration Test is suitable for soft soils; in apposite, the Plate Load Test is more suitable for coarse-grained soils. There are some unavoidable disadvantages for experimental methods, these tests can be expensive and time-consuming, and some have limitations with certain soil types, such as Standard Penetration Test in clays or coarse-grained soils. They are accurate for local conditions and their reliability can be different which is the reason that they are often combined with analytical methods for a more complete design.

Eurocode 7 combines theory, experimental data, and partial safety factors to provide a standardized framework across Europe. It includes equations for drained and undrained conditions and applies unique design approaches such as DA1 (double-checking with two combinations), DA2 (resistance-focused), and DA3 (conservative for weak soils).

This approach balances theory and practice and considers uncertainties in both loads and ground conditions, also it ensures regulatory compliance for example, DA2 has been used in the design of wind turbine foundations under dynamic loads or spread foundations. Eurocode 7 is highly dependable because of the safety factors, and it can be more conservative than pure analytical methods and it requires expertise to apply effectively.

7 Conclusion

This thesis has explored a comprehensive examination of the bearing capacity of shallow foundations and comparing the methods to calculate it. It reviews foundation types such as pads, strips, combined, cantilever and mats; Their dictation from deep foundations using the depth-to-width ratio. The foundations established for understanding soil acting under applied loads.

Calculation methods have been explored starting with the analytical methods. In Terzaghi's theory, it is assumed based on general shear failure and gives formulas for strip, square, and circular foundations by using the key bearing capacity factors (Nc, Nq, Nγ). Meyerhof's approach improves Terzaghi's method by adding real-world observation like foundation shape, depth, and inclined loads. Meyerhof's method makes it more flexible and user-friendly. These analytical tools are great because they're fast and cheap for initial planning on even soils, but they can be very conservative in problematic situations because of their built-in assumptions.

The next section is experimental methods, like the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Plate Load Test (PLT). These methods take data from the actual site by considering aspects like soil layers that formulas might miss. They are useful for in-depth checks, but they are time consuming, expensive, and their results can depend on scale, so they are beneficial as backups to other methods rather than the main method.

Eurocode 7, which blends semi-empirical formulas for both drained and undrained soils, includes factors for bearing resistance and corrections for off-centre loads, shapes, and slopes. The design approaches, DA1 for double-checking, DA2 for a balanced, practical phase, and DA3 for when the ground is unpredictable.

Each approach has its own strengths and weaknesses. Analytical methods are based on strong theoretical bas but can sometimes improve results in layered soils. Experimental methods provide detailed insights, even though they usually need to be combined with analysis for a full picture. Eurocode 7 provides standardized safety framework, even if it can be complex or conservative. Its advantage is in linking theory with practical application and it is especially useful in cases like wind turbine foundations, where overturning forces and cycling loading are critical factors.

Overall conclusion can be combining the methods together which can result in reliable foundation design. Comprehensive and understandable site investigations are essential to confirm assumptions and ensure safety in challenging soil conditions. Nevertheless, this study has certain limitations because it only focuses on shallow foundations does not cover any major computer simulations or practical case studies. In the future, more research in this field can expand this topic by exploring advanced numerical analysis or machine learning models. Comparing future methods with the methods studied in this thesis can result in the best an efficient foundation design.

In the end, bearing capacity concept is important to avoid collapses, failures and smarter built for the future. This thesis contributes to the field by adding various design methods with their practical applications, advocating for a comprehensive approach that prioritizes safety, informed decision-making, and adaptability in geotechnical engineering.

Reference

Cone Penetration Testing (CPT). (n.d.). Retrieved August 25, 2025, from https://www.geoengineer.org/education/site-characterization-in-situ-testing-general/cone-penetration-testing-cpt

Cuffaro, F. (2024, September 6). Standard Penetration Test (SPT): Critical for Foundation Design. *DiLandro Andrews*. https://dilandroandrews.com/standard-penetration-test/

Eurocode 7: Geotechnical design—Part 1: General rules. (2004, April 23).

Fauzi, J. (2016). *Procedure of Standard Penetration Test*. ResearchGate. https://www.researchgate.net/figure/Procedure-of-Standard-Penetration-Test_fig3_338491449

Finnish national annex, Design of foundations, instructions. (n.d.).

Frank, R., & Kavvadas, M. (2004). *Designers-guide-to-eurocode-7-geotechnical-design-EN-1997*.

Laying a Firm Foundation: A Detailed Examination of Mat or Raft Systems in Construction – U-Property PH. (n.d.). Retrieved August 19, 2025, from https://upropertyph.com/2023/09/07/laying-a-firm-foundation-a-detailed-examination-of-mat-or-raft-systems-in-construction-2/

Lees, A. (2019, November 14). *Plate Load Tests—Uses, Plate Size and Interpretation*. https://www.tensarinternational.com/resources/articles/plate-load-testing-size-matters

Lees, A. (2021, February 18). *Bearing Capacity of Soil: Types and Calculations* | *Tensar*. https://www.tensarinternational.com/resources/articles/bearing-capacity-of-soil

M.Das, B. (2019). *Principle of foundation engineering*.

Pad Footing Analysis—Structural Engineering Design Centre. (n.d.). Retrieved August 19, 2025, from https://sedc.com.au/Calculators/Calc5

Plate Load Testing | Plate Bearing Test. (n.d.). *Alliance Geotechnical*. Retrieved August 25, 2025, from https://allgeo.com.au/geotechnical/inspections-monitoring/plate-load-testing/

Prasad. (2022, April 26). Strap Footing types and design procedure. *Structural Guide*. https://www.structuralguide.com/strap-footing/

Shree TMT. (2024, May 17). All About Shallow Foundation: Definition & Types (Complete Guide). *Best TMT Steel in Hyderabad | TMT Steel in Hyderabad | ShreeTMT |*. https://www.shreetmt.com/all-about-shallow-foundation-and-types/

Soil Bearing Capacity: Terzaghi and Meyerhof | CalcTree. (2025, September 4). CalcTree. https://www.calctree.com/resources/bearing

Strip Footing. (n.d.). Retrieved August 19, 2025, from http://www.builderbill-diy-help.com/strip-footing.html

Tomiša, A. (2019, June 13). Cone Penetration Test with pore water pressure measurement (CPTU). *Geotech*. https://www.geotech.hr/en/cone-penetration-test-with-pore-water-pressure-measurement-cptu/

Truong, T. (2024, August 23). Factors Affecting Bearing Capacity of Soil. *Ideal Geotech*. https://idealgeotech.com.au/factors-affecting-bearing-capacity-of-soil/

What are Combined Footings? | Gharpedia. (n.d.). Retrieved August 19, 2025, from https://gharpedia.com/blog/what-are-combined-footings/