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"Comparative Analysis of Bearing Capacity Evaluation Methods for Shallow Foundations"

1 Pradeep Jatav, 2Prof. Ashish shrivas,
1M.Tech Student,[2]Assistant Professor,
[1,2,]Civil Engineering Department,
[1,2,]Vikrant University, Gwalior, (M.P.) India

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ABSTRACT: Shallow foundations are widely used to transfer structural loads safely to the ground while maintaining stability and controlling settlement. This study presents a comparative evaluation of different methods used to determine the bearing capacity of shallow foundations, including analytical, experimental, and code-based approaches.
The research reviews common shallow foundation types and discusses factors affecting bearing capacity, such as soil properties, loading conditions, and foundation depth. Analytical methods, including Terzaghi's and Meyerhof's theories, are examined alongside experimental techniques such as the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Plate Load Test (PLT). The study also investigates the design provisions of Eurocode 7, which incorporates safety factors and multiple design approaches to ensure reliable foundation performance.
A comparison of these methods shows that analytical approaches are simple and economical, experimental methods provide accurate field-based results, and Eurocode 7 offers a standardized and safe design framework. The findings emphasize that combining these approaches with proper site investigation leads to more efficient and reliable foundation designs.

Keywords: Shallow Foundations, Bearing Capacity, Terzaghi Theory, Meyerhof Theory, Eurocode 7, Foundation Design.

INTODUCTION: 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.

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)

LITERATURE REVIEW:

Terzaghi (1943)MKarl Terzaghi proposed the first comprehensive theory for the bearing capacity of shallow foundations. The theory was developed for strip footings under general shear failure conditions.

Main assumptions:

- Soil is homogeneous and isotropic.
- Foundation is shallow and rough.
- Load acts vertically and centrally.
- Failure surface develops beneath the footing.

Terzaghi introduced three bearing capacity factors:

- N_c
- N_q
- N_γ

The theory became the foundation for later developments in bearing capacity analysis.

Meyerhof (1951–1963) George Geoffrey Meyerhof improved Terzaghi's equation by incorporating:

- Shape factors
- Depth factors
- Inclination factors

Meyerhof's method can be applied to:

- Strip footings
- Square footings
- Circular footings

Researchers found that Meyerhof's approach gives comparatively conservative and realistic results for practical field conditions**.**

Hansen (1970)J. Brinch Hansen further modified the bearing capacity equation by considering:

- Ground inclination
- Base inclination
- Load eccentricity
- Shape correction

Hansen's method became useful for complex loading and sloping ground conditions.

Vesic (1973–1975) Aleksandar Vesic proposed improved bearing capacity factors and introduced a more realistic failure mechanism. Vesic's theory is widely considered more accurate for cohesionless soils and layered soil conditions.

Several studies concluded that Vesic's method generally predicts higher bearing capacity values compared to Terzaghi and Meyerhof**.**

B. M. Das (2007) Das discussed analytical and empirical approaches for shallow foundation design and compared different bearing capacity equations.

Major Findings:

- No single method is universally accurate.
- Soil properties significantly influence predictions.
- Recommended using factor of safety carefully.

Finite Element Study using PLAXIS (2015) Researchers compared analytical methods with finite element modeling using PLAXIS software.

Major Findings:

- FEM provides more realistic stress distribution.
- Classical methods overestimate bearing capacity in layered soils.
- Numerical methods better simulate soil-structure interaction.

Comparative Study on Layered Soils (2018)A study compared Terzaghi, Meyerhof, and Vesic methods for layered soil conditions.

Major Findings:

- Classical equations are less accurate for layered soils.
- Upper weak layers significantly reduce bearing capacity.
- Vesic's method showed comparatively better agreement with FEM results

Recent Comparative Analysis by Pantelidis (2024) Pantelidis performed a detailed comparison of classical bearing capacity equations and numerical methods for shallow foundations.

Major Findings:

- Vesic's method produced the closest results to numerical simulations.
- Hansen's method showed larger variability.
- Unified depth factors improved prediction accuracy.
- Numerical methods are preferred for complex geotechnical conditions**.**

BEARING CAPACITY OF SOILS 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 valuewhich 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 qu, 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)

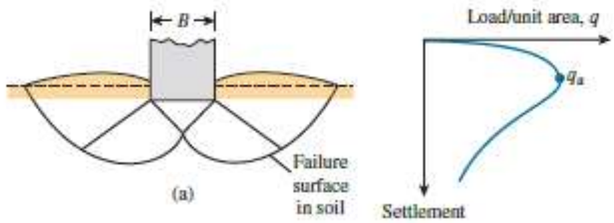

Figure 6. General shear failure (M.Das, 2019, p. 208)

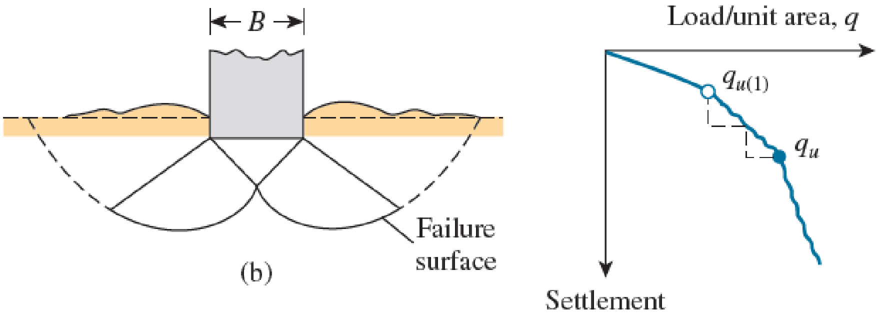

Figure 7. Local shear failure(M.Das, 2019, p. 208

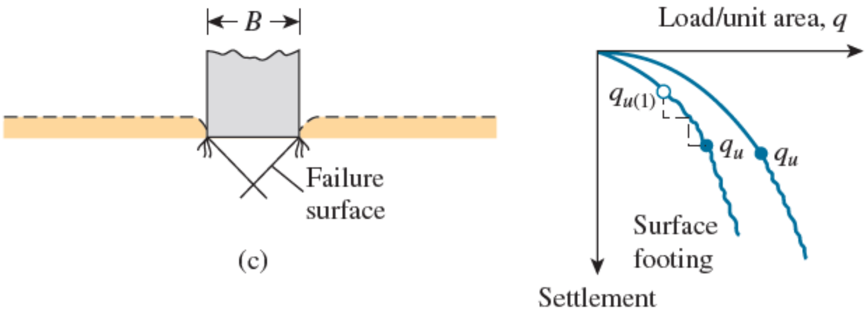

Figure 8. Punching shear failure(M.Das, 2019, p. 208)

METHODS AND EXPERIMETAL APPROACH

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.

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 (Df) 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 (DfB). 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 $q=\gamma\times Df$, 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.

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 Cu
- 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

CONCLUSIONS

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 (N_c, N_q, N_γ). 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 toconfirm 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.

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