Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter literature reviews are presented on the following three topics: (a) limit analysis, (b) ring footings, and (c) unsaturated bearing capacity of strip footings. The first section presents a comprehensive review of the progress made in numerical upper and lower bound limit analysis. This section emphasizes the advancements carried out in limit analysis through the incorporation of different mathematical optimization techniques, different forms of finite elements, material nonlinearities, solution strategies, and so on. The subsequent section features the articles addressing the determination of the ultimate bearing capacity of the ring footing resting on single or multilayered soils. This section includes all the findings concerning the ring footings through experimental, analytical, and numerical studies. The third section highlights the articles related to the bearing capacity determination of strip footing resting on unsaturated soils. Following this, the research gaps and objectives of the current thesis are elucidated.

2.2 LITERATURE REVIEW: LIMIT ANALYSIS

The limit theorem was first introduced in the field of geotechnical engineering in the late sixties of the previous century. This method appears to be more rational and accurate in comparison to its contemporary finite element approach. Since its inception, limit analysis has undergone significant advancement through the integration of finite element methods, nonlinearity, and robust optimization techniques. Several plane strain and axisymmetric structures are rigorously analyzed, thereafter. The development of limit analysis has later transitioned from two-dimensional to three-dimensional (3D) analysis, allowing for more realistic modeling of soil structures. The progresses made in 2D limit analysis were further extended to 3D limit analysis. With advancements in technology, three-dimensional modeling became feasible, providing more accurate stress and strain distribution. Limit analysis has been successfully applied to various stability problems in geotechnical engineering. Some of the major contributions to the evolution of limit analysis have been mentioned below:

2.2.1 Hayes and Marcal (1967)

Hayes and Marcal (1967) made significant contributions to upper bound analysis by developing one of the earliest mathematical programming formulations that incorporated finite element discretization of the velocity field. Their method focused on determining the maximum collapse load of flat plates with features such as narrow slits, holes, and V-notches. The optimization process in their approach involved assuming a kinematically feasible velocity field and then adjusting it to minimize the collapse load. They employed triangular finite elements with linear velocity variations to model the deformation behavior of the plate. The authors recommended using smaller elements in areas with high-stress concentrations and larger elements in regions where rigid body movements were expected, aiming to achieve accurate results across the plate.

2.2.2 Lysmer (1970)

Lysmer (1970) was a pioneer in proposing the use of finite elements and linear programming for computing lower bound solutions in plane strain stability problems in geotechnical engineering. The discretization of soil was done using triangular elements, with linearly varying nodal normal and shear stresses treated as unknown variables. Statically admissible stress discontinuities were allowed at the interfaces between adjacent triangles to model stress variation in the soil domain. The non-linear Mohr-Coulomb yield function was linearized using a polygonal approximation. The process of linearizing the yield function in Lysmer's method introduced a significant number of constraints, which, in turn, led to extensive computational time. This approach by Lysmer laid the foundation for using finite elements and linear programming to obtain lower bound solutions in geotechnical stability problems.

2.2.3 Anderheggen and Knopfel (1972)

Anderheggen and Knopfel (1972) expanded upon the work of Lysmer (1970) by presenting a formulation for numerical lower and upper bound methods using finite elements and linear programming. In their lower bound formulation, the objective was to maximize the load factor with respect to body and surface forces which gives the collapse load magnitude. The revised simplex algorithm was employed to efficiently carry out the linear optimization process. For upper bound analysis, they introduced two models: i) one with a linear deflection and bending moment variation, and ii) a linear deflection variation and a constant moment distribution over the element. The revised simplex algorithm was utilized in both models.

2.2.4 Basudhar et al. (1979)

Basudhar et al. (1979) used nonlinear programming to modify Lysmer (1970) lower bound limit analysis method to incorporate nonlinear yield condition directly in the analysis. In this method, the equilibrium conditions formed a set of linear constraints, while the yield conditions resulted in a set of nonlinear constraints. Using Kavlie (1971) penalty function method, the constrained minimization problem was transformed into an unconstrained minimization problem in this approach. Finally, the objective function was then solved using unconstrained minimization technique proposed by Powell (1964) algorithm. The methodology was applied to solve passive earth pressure problems.

2.2.5 Bottero et al. (1980)

Boterro et al. (1980) modified the static and kinematic approaches for solving plain stain stability problems developed by Maier et al. (1972) and Anderheggen and Knoppel (1972) respectively. The soil mass was discretized into three-noded triangular elements and used linear shape functions as proposed by Lysmer (1970). The Mohr-Coulomb yield surface was approximated by external polyhedral approximation for the upper bound and internal polyhedral approximation for the lower bound. The main objective was solved by linear optimization with the revised simplex algorithm. The formulation was applied successfully to analyze the collapse load of smooth strip footings, ultimate pullout resistance of foundations in cohesive soil, and stability of slopes in cohesive soils.

2.2.6 Pastor and Turgeman (1982)

Pastor and Turgemen (1982) built upon the plane strain formulation proposed by Bottero et al. (1980) to address axisymmetric geotechnical engineering problems using lower bound finite element limit analysis. In order to maintain element equilibrium, they used a unique variation of the stresses within each element base by Harr-Von Karman hypothesis. They extended the formulation to accommodate both the von Mises and Mohr-Coulomb yield criteria and introduced a total of $3p$ inequality constraints at all nodes, where p represents the number of sides of the chosen polyhedrons for yield surface linearization.

2.2.7 Arai and Tagyo (1985)

Arai and Tagyo (1985) introduced a new numerical lower bound method that involved the use of constant stress elements. The method employed a nonlinear yield condition and a nonlinear programming technique, sequential unconstrained minimization technique (SUMT), along with the conjugate gradient algorithm of Fletcher and Reeves (1964). However, this method has some limitations, including the impossibility of accurately specifying the soil-footing interface condition, the risk of a local minimum solution with SUMT, and the restriction to soils with low friction angles.

2.2.8 Sloan (1988)

Sloan (1988) developed a novel method for computing rigorous lower bounds on collapse loads in geotechnical engineering, building upon the approach introduced by Bottero et al. (1980). The method involved discretizing the stress field using three-noded triangular elements. Sloan (1988) considered stress discontinuities along all interfaces of the triangular elements. By linearizing the Mohr-Coulomb yield criteria, as outlined by Bottero et al. (1980), a statically admissible stress field was obtained through linear optimization. To solve the associated linear programming problem, Sloan (1988) employed an active set algorithm, which took advantage of the sparse nature of the resulting matrix. This algorithm proved advantageous in terms of computational efficiency, resulting in reduced computation time compared to traditional simplex or revised simplex algorithms.

2.2.9 Sloan (1989)

Sloan (1989) introduced a method for obtaining rigorous upper bounds on collapse loads in cohesive and frictional soils under plane strain conditions. Kinematically permissible velocity discontinuities were restricted to certain planes, and the soil was separated into triangle components placed in quadrilateral pattern. After linearizing the yield surface using a regular polygon, the upper bound finite element problem was created using linear programming. This programming was done using the active set technique.

2.2.10 Sloan and Kleeman (1995)

Sloan and Kleeman (1995) introduced a novel method that computed upper bounds under plane strain conditions. The method utilized a linear triangular element with six unknown nodal velocities and a fixed number of plastic multiplier rates. Unlike previous approaches, this method allowed for velocity discontinuities at all shared edges of adjacent triangles, with their shearing directions determined automatically. Additional unknowns were used to describe the velocity jump along each discontinuity. It was applicable to various material types and required fewer elements compared to existing methods. Overall, the method was an efficient and versatile approach for obtaining rigorous upper bound solutions.

2.2.11 Lyamin and Sloan (2002a)

Lyamin and Sloan (2002a) proposed a comprehensive formulation for determining lower bound solutions for collapse loads. Their method incorporated linear finite elements and non-linear programming, making it applicable to problems in one, two, or three dimensions. They recognized the limitations of linearizing the yield criteria, which resulted in a large number of constraints and restricted the search region. To overcome these limitations, they enforced the yield condition in its non-linear form. To ensure the double differentiation of yield function, they utilized a smoothed version of the Mohr-Coulomb criteria suggested by Abbo and Sloan (1995). The non-linear programming problem was solved using a modified two-stage quasi-Newton algorithm, which improved the efficiency compared to the equivalent linear programming formulation presented by Sloan (1988), especially in two-dimensional problems.

2.2.12 Lyamin and Sloan (2002b)

Lyamin and Sloan (2002a) proposed a method similar to their earlier work in 2002 for computing upper bound solutions using linear finite elements and non-linear programming. They addressed the limitations associated with linearizing the yield criteria by employing a smoothed version of the Mohr-Coulomb criteria. To solve the non-linear programming problem, they utilized a two-stage quasi-Newton technique, which demonstrated faster performance compared to linear programming, particularly in two-dimensional scenarios. The formulation developed by Lyamin and Sloan has found practical applications in the assessment of plate anchor stability in clays and the determination of bearing capacity for footings on sand

2.2.13 Krabbenhoft and Damkilde (2003)

Krabbenhoft and Damkilde (2003) presented a non-linear programming algorithm for solving the discrete lower bound limit analysis problem without the need to linearize the yield criteria. The algorithm utilized an interior point method that was entirely general and independent of specific finite element discretization or yield criteria. Similar to interior point methods for linear programming, the number of iterations was minimally affected by the problem size. The authors employed duality theory and interpreted the Lagrange multipliers used in the algorithm as representative of the displacements and strains at collapse. The method's generality and efficiency were validated through examples involving plate and slab structures governed by various non-linear yield criteria.

2.2.14 Krabbenhoft et al. (2005)

Krabbenhoft et al. (2005) introduced a new upper bound limit analysis formulation for solids in 2D and 3D. In contrast to traditional methods, their approach was formulated based on stresses rather than velocities and plastic multipliers. The method allowed for kinematically admissible velocity discontinuities along inter-element boundaries, following the approach of Sloan & Kleeman (1995), but expressed in terms of nodal stresses rather than velocities. The discontinuities were modeled as two thin triangular elements. The proposed formulation was applied to study the stability of slopes and conical excavations in 2D and 3D, respectively.

2.2.15 Makrodimopoulos and Martin (2006)

Makrodimopoulos and Martin (2006) presented a formulation of lower bound limit analysis using second-order cone programming (SOCP). Their method offered strict lower bound solutions and utilized efficient primal-dual interior-point algorithms that had been recently developed for SOCP. The formulation was applicable to a wide range of yield criteria, including popular ones such as Mohr-Coulomb, Drucker-Prager (including von Mises), and Nielsen's criterion for plates. The authors focused on cohesive and cohesive-frictional problems in plane strain for their initial study. By employing an efficient algorithm based on the interior-point method, they demonstrated the speed and stability advantages of using SOCP for limit analysis.

2.2.16 Makrodimopoulos and Martin (2007)

Makrodimopoulos and Martin (2007) presented a novel finite element method for upper bound limit analysis. They formulated the optimization of the displacement field as a second-order cone programming (SOCP) problem, enabling efficient and fast solution using state-of-the-art algorithms. The method was demonstrated on plane strain problems with the Mohr-Coulomb criterion, but it was applicable to three dimensions with the Drucker-Prager criterion and other yield criteria following a conic quadratic form. The SOCP formulation allowed for accurate solutions and eliminated the need for ad hoc smoothing strategies. The study emphasized the computational benefits and potential for further advancements in incorporating discontinuities and developing mesh adaptivity strategies.

2.2.17 Krabbenhoft et al. (2007)

Krabbenhoft et al. (2007) introduced a novel three-dimensional finite element limit analysis approach based on the work of Lyamin and Sloan (2002b) and Makrodimopoulos and Martin (2006). They focused on enforcing the three-dimensional Mohr-Coulomb yield criterion without any smoothing, in contrast to previous methods. The optimization problem arising from this formulation was solved using semi-definite programming techniques, with the Mohr-Coulomb criteria represented as a set of semi-definite constraints. The researchers applied their method to compute the bearing capacity of circular and square footings on frictional soils and assess the stability of conical excavations in cohesive frictional soils.

2.2.18 Kumar and Khatri (2011)

Kumar and Khatri (2011) presented a new method for solving axisymmetric stability problems by using lower bound finite element limit analysis and linear programming. This method was based on the concept proposed by Sloan (1988) and involved treating nodal stresses (σ_r, σ_z, τ_{rz}, σ_θ) as the main unknown variables. The number of inequality constraints was reduced from $3p$ to $(p+3)$ at each node, which was a departure from the approach taken by Pastor and Turgeman (1982). The Haar–von Karman (1909) hypothesis was assumed to be valid, implying that the hoop stress (σ_θ) would be equal to one of the in-plane principal stresses. The optimization process was performed using the LINPROG function in MATLAB, with a set of linear equality and inequality constraints. This approach was successfully applied to several axisymmetric geotechnical stability problems.

2.2.19 Kumar and Chakraborty (2013)

Kumar and Chakraborty (2013) created a numerical method for addressing axisymmetric stability problems by using linear optimization, lower bound limit analysis, and finite elements. They approximated the Drucker-Prager (DP) yield criterion by modeling a sphere with an inscribed truncated icosahedron with 60 vertices and 32 faces. The MC yield criterion was also linearized by replacing the three cones with interior polyhedrons, as previously suggested by Pastor and Turgeman (1982). These two formulations were then used to determine the collapse loads for both smooth and rough circular footings resting on cohesive-friction material with non-zero unit weight.

2.2.20 Chakraborty and Kumar (2014)

Chakraborty and Kumar (2014) introduced a new method to solve axisymmetric stability problems in geomechanics using the DP yield criterion and upper bound limit analysis. To achieve this, they linearized the DP yield surface using a circumscribed truncated Icosahedron with 32 faces and 60 vertices. This numerical formulation uses only the velocities and plastic multiplier rates as the basic unknown variables, and is used to determine the collapse loads of circular footings placed on cohesive-frictional materials. The results of the proposed formulation have been found to be quite satisfactory, especially for lower values of ϕ.

2.2.21 Chakraborty and Kumar (2015)

A method has been developed by Chakraborty and Kumar (2015) to address an axisymmetric geomechanics stability problem using a two-dimensional finite element lower-bound limit analysis formulation and the three-dimensional Mohr-Coulomb yield criterion. Nonlinear optimization was employed to solve the problem, and the interior point method (IPM) based on the logarithmic barrier function was used for the optimization. This approach does not rely on any assumptions with the computation of circumferential stress (σ_θ). To improve the yield surface, the apex of the pyramid in the meridian plane was smoothed by removing the tip singularity, and the stress discontinuities at the corners of the yield hexagon in the π-plane were eliminated. Using this method, the bearing-capacity factors N_c, N_q, and N_γ for different values of ϕ were calculated for a circular footing.

2.2.22 Mohapatra and Kumar (2018)

Mohapatra and Kumar (2018) developed a new method using upper bound finite elements limit analysis and semi-definite programming, following a similar approach to Tang et al. (2014). They employed three-noded constant strain and six-noded linear strain finite elements to produce solutions for axisymmetric stability problems based on the Mohr-Coulomb yield criteria. The formulation considered nodal velocities and element plastic strain rates as the primary governing variables and included velocity discontinuities at all element interfaces. Using this new method, they were able to calculate the bearing capacity of smooth and rough circular footings.

2.2.23 Ukritchon and Keawsawasvong (2018)

For the anisotropic undrained strength requirements of soils, Ukritchon and Keawsawasvong (2018) introduced a new lower bound limit analysis approach. The anisotropic undrained strength of clay was represented by their method, which used finite element modelling with triangular elements and an elliptical yield criterion. They established equilibrium equations and stress boundary conditions while remaining within the strength envelope by defining a statically permissible stress field within each element and along shared edges between adjacent elements. The authors used second-order cone programming to create the lower bound solution, and they verified their methodology by contrasting model predictions with the exact solutions of strip footings and the undrained stability of a shallow unlined square tunnel.

2.3 LITERATURE REVIEW: ULTIMATE BEARING CAPACITY OF RING FOOTING

This section covers the literature review of ring footing resting on single and multilayered soil stratum. The section highlights the articles that explore the determination of the ultimate bearing capacity of ring footings through experimental as well as theoretical works. The influence of the size of ring footing, applied surcharges, thickness of upper soil (in case of double layer stratum), and strength parameter of underneath soil has been elaborately reviewed.

2.3.1 Ismael (1995)

Ismael (1995) conducted plate load tests on very dense cemented sands at a flat site in Kiefan, Kuwait to investigate the behavior of ring foundations. The tests were performed on 0.6 m diameter solid and ring plates, located 0.4 m below ground level, with inside-to-outer ring plate radii ratios (r_i/r_0) of 0.25, 0.5, and 0.75. The effective soil strength parameters c' and ϕ' were 31 kPa and 36°, respectively. The study aimed to determine the settlement ratio variation with the width ratio for cemented sands, and load-settlement curves for solid and ring plates were compared, emphasizing elastic settlement and ultimate bearing capacity. The results showed that ring plates exhibited smaller settlement at all pressures than solid plates, but there was little to no change in bearing capacity. Additionally, tests were conducted on 0.45 m and 0.3 m diameter solid plates.

2.3.2 Boushehrian and Hataf (2003)

Boushehrian and Hataf (2003) conducted laboratory and numerical simulations to examine the effectiveness of ring footings on reinforced sand. The bearing capacity of foundations was studied based on the depth of the first layer of reinforcement, vertical spacing, and the number of reinforcement layers. Their experimental and computational results demonstrated an optimal reinforcement embedment depth corresponding to the most significant bearing capacity using a single reinforcement layer. There appeared to be an optimum vertical spacing of reinforcing layers for multi-layer reinforced sand. If the reinforcements were placed within a range of effective depths, the bearing capacity increased with increasing reinforcement layers. Furthermore, the analysis revealed that increasing reinforcement stiffness above a certain threshold does not increase bearing capacity.

2.3.3 Hataf and Razavi (2003)

Hataf and Razavi (2003) conducted research to investigate the ultimate bearing capacity of model ring footings under various conditions such as the ratio of internal to external diameter (r_i/r_0), base roughness, and thickness of the sand layer. The study explored the failure pattern beneath the footing and established a semi-empirical relationship for determining the bearing capacity of ring footings. In addition, the researchers used the finite element method to calculate the bearing capacity of the footings. The results of the experimental, semi-empirical, and numerical methods were compared, and reasonable agreement was observed.

2.3.4 Kumar and Ghosh (2005)

Kumar and Ghosh (2005) employed the stress characteristics method to determine the bearing capacity factor (N_γ) for smooth and rough ring footings. The study assumed that the interface friction angle (δ) between the footing base and the underlying cohesionless material gradually increases from zero along the axis of symmetry to the outer edge of the footing for rough foundations. They found a considerable decrease in the N_γ value with an increase in r_i/r_0, where r_i and r_0 are the ring's inner and outer radii. Moreover, the N_γ value for a rough footing was significantly higher than that for a smooth foundation for higher ϕ values.

2.3.5 Zhao and Wang (2008)

The ultimate bearing capacity of ring footings was determined numerically by Zhao and Wang (2008) using the finite-difference code FLAC. Their study considered cohesionless, frictional, and weighty soil for analysis, which was modeled as an elasto-plastic material following Mohr-Coulomb's yield criteria and associative flow rule. The computed bearing capacity factor (N_γ) was found to decrease with an increase in the internal to external radius (r_i/r_0). Additionally, the N_γ values were significantly higher for a rough ring footing than for a smooth one, particularly for higher ϕ values.

2.3.6 Demir et al. (2012)

Demir et al. (2012) have conducted a series of field tests on ring footings on natural clayey deposits and found that the ring footing, with the optimum value of inner to outer radius ratio, performs in a manner similar to that of a full circular footing with its diameter same as that of the outer diameter of the ring foundation. Demir et al. (2012) reported that the bearing capacity decreases rapidly for r_i/r_o ratio varying from 0 to 0.3 and then it decreases at a slower rate when this ratio changes from 0.3 to 0.6.

2.3.7 Benmebarek et al. (2012)

Benmebarek et al. (2012) used the FLAC code to calculate the bearing capacity factor N_γ for ring footings on sand with smooth and rough surfaces, taking into account associated and non-associated Mohr-Coulomb soils. They obtained results that were similar to those of Zhao and Wang (2008) regarding the variation of N_γ for ring footings. The study also found that soil dilation angle affects N_γ values when the soil exhibits high non-associativity and large internal friction angle values. The computational results were presented using design tables and graphs. It was concluded that the soil dilation angle plays an important role on the value of N_γ especially when the value of ϕ becomes greater than 30°.

2.3.8 Moayed et al. (2012)

Moayed et al. (2012) presented a numerical simulation to calculate the ultimate bearing capacity of a two-layer soil beneath a rigid ring footing. The soil is modeled as an elastic-plastic material following the Mohr-Coulomb yield criterion, and the bearing capacity of the footing is determined using ABAQUS finite element software. The simulation results show that the bearing capacity decreases as the r_i/r_0 ratio increases. The study also found that as the depth of the clay layer beneath the footing increases, the bearing capacity decreases gradually. Moreover, increasing the r_i/r_0 ratio has no significant effect on the bearing capacity with changing clay layer thickness. The displacement vector field analysis showed that as the depth of the clay layer increases, the displacement vectors tend to propagate within the clay layer and do not enter the sand region. Conversely, as the depth of the clay layer decreases, the displacement vectors are confined to the clay layer. In conclusion, the studies on ring footings underscore the critical role played by various factors in determining their bearing capacity and settlement. The radii ratio, particularly with an optimum value of 0.4, stands out as a significant influence on performance.

2.3.9 Sawwaf and Nazir (2012)

Sawwaf and Nazir (2012) conducted a study on the behavior of a model ring footing subjected to eccentric loads, resting on a compacted replaced layer of sand over a loose sand layer. The researchers suggested that reinforcing the replaced sand layer with geogrid reinforcement could be beneficial. The study involved various load configurations to simulate ring footings under vertical and lateral loads causing overturning moments. radius ratios and load eccentricities were tested using several geogrid layers, numbers, and stiffness configurations. The study also examined the effect of the depth and relative density of the replaced sand layer. The results showed that the best number of layer was 3 layers, and after that the rate of bearing capacity enhancement seems to be steady. The inclusion of soil reinforcement led to a considerable reduction in the depth of the replaced sand layer and a significant increase in the bearing capacities of the eccentrically loaded rings (e/r_0=0.3).

2.3.10 Naseri and Hosseininia (2015)

Naseri and Hosseininia (2015) utilized the finite difference method to conduct numerical computations and investigate the settlement of ring foundations on an elastic half space. The researchers employed displacement influence factors, commonly used in elasticity theory, to calculate the settlement of a ring footing. The study considered various factors affecting the influence factors, including ring geometry, footing stiffness, footing embedment, and soil non-homogeneity. The researchers assumed that the soil elastic modulus increases linearly with depth. The study presented computational results in the form of graphs and proposed mathematical expressions for the influence factors to be used in practical applications for the analysis and design of ring footings. The results were compared with published numerical and analytical data for the influence factors of circular footings to verify the accuracy of the findings.

2.3.11 Kumar and Chakraborty (2015)

Kumar and Chakraborty (2015) used lower and upper bound theorems of limit analysis, which are mathematical methods for predicting the ultimate load carrying capacity of a structure, in conjunction with finite elements and linear optimization to compute the bearing capacity factors for smooth and rough ring footings with different radius ratios (r_i/r_0). The analysis revealed that the collapse load, which is the maximum load a foundation can bear before it fails, decreased continuously as the inner radius (r_i) of the footing increased for a smooth footing with a given outer radius (r_0). However, for a rough footing with a given outer radius, there was almost no reduction in the collapse load for r_i/r_0 ratios up to 0.2. For r_i/r_0 ratios greater than 0.2, the collapse load for a rough footing also decreased continuously with increasing r_i/r_0 ratios, similar to that of a smooth footing.

2.3.12 Keshavarz and Kumar (2017)

Keshavarz and Kumar (2017) used the stress characteristics method to assess the ultimate bearing capacity of smooth and rough ring foundations. Stress singularities at both the inner and outer edges of the ring footing were also considered to obtain solutions. The study analyzed two mechanisms for a smooth footing and four mechanisms for a rough footing. Additionally, slip line patterns and stress distributions beneath the ring footing examined in different scenarios. The study presented the bearing capacity factors, N_c, N_q, and N_γ for smooth and rough ring foundations as a function of ϕ and r_i/r_0. For rough footing, the bearing capacity factors tend to peak at a certain value of r_i/r_0, which generally lies between 0.1 and 0.5. However, for smooth footing, the bearing capacity factors N_c and N_q decrease continuously with increasing r_i/r_0.

2.3.13 Benmebarek et al. (2017)

Benmebarek et al. (2017) used FLAC code to conduct numerical simulations to investigate the impact of both the radius ratio (r_i/r_0) of the ring footing and the embedment ratios up to unity on the undrained bearing capacity factor (N'_c) for various roughness conditions. The study revealed that there is hardly any reduction in the value of N'_c for both smooth and rough surface ring footings with an increase in the ratio r_i/r_0 up to 0.25. However, for r_i/r_0 =0.25, the values of N'_c decrease significantly with an increase in r_i/r_0. Additionally, for embedded ring footing with rough sides, the results indicate that the difference in bearing capacity between circular and ring footings decreases as the embedment depth increases. For example, for $r_i/r_0 = 0.5$, the difference disappears completely for an embedment ratio of 0.5. The analysis results are reasonably consistent with theoretical data available in the literature.

2.3.14 Gholami and Hosseininia (2017)

Gholami and Hosseininia (2017) utilized the method of characteristics is employed to transform hyperbolic differential equations into a set of ordinary differential equations. These equations are the foundation for the code that is used to calculate the bearing capacity of ring footings with smooth and rough bases. The soil examined in this study follows the Mohr-Coulomb yield creation and is cohesive-frictional, including unit weight and surcharge. Bearing capacity factors, N_c, N_q, and N_γ, are determined for various soil conditions. The study provided a comprehensive set of bearing capacity factors for different ratios of internal radius to external radius of the ring footings and a wide range of internal friction angles. Based on the analysis of these values, equations are suggested for these factors. The results show that the bearing capacity of ring foundations can be calculated by using the calculated bearing capacity factors in a superposition equation. The average differences between the bearing capacity values obtained from these methods are 10%. The N_γ values of the ring footing are compared to previous studies, while no similar studies are available to compare the N_q and N_c of the ring footing. Thus, the calculated bearing capacity factors N_q and N_c by the written code for circular footings ($r_i = 0$) are compared with other studies.

2.3.15 Tang and Phoon (2018)

Tang and Phoon (2018) utilized OptumG2 to assess the bearing capacity of ring foundations on dense sand. They compared their findings with plasticity solutions, numerical analyses, laboratory small-scale model tests, and field plate loading tests from previous research. To account for the dependence of the friction angle on the stress level, they employed the Bolton strength–dilatancy relation. The results of the study agreed well with centrifuge model tests for solid circular footings. However, a significant discrepancy was observed between numerical analyses and centrifuge model tests for the ring foundation, particularly when the radii ratio r_i/r_0 exceeded 0.35. As a solution, the authors suggested an alternative method where a resistance ratio of the ring foundation to the solid circular footing r_i/r_0 =0 with the same size is applied to an approximate equation for the bearing capacity of the solid circular footing regarding the stress level effect. This proposed approach was verified with centrifuge model tests.

2.3.16 Chavda and Dodagaudar (2019)

Chavda and Dodagaudar (2019) utilized the Finite Element Method (FEM) to determine the bearing capacity factors (N_c, N_q, *and* N_γ) for smooth and rough ring footings. They calculated the bearing capacity factors using the axisymmetric and plane strain formulation for r_i/r_0 = 0 to 0.98 and r_i/r_0 = 1 (strip footing), respectively. They analyzed a problem with specified values of cohesion, surcharge, and unit weight to determine the trend of the ultimate bearing capacity of the ring footing for radius ratios ranging from 0 to 1. The optimum value of N_c at the ratio of radius equal to 0.25 for rough base footing.

2.3.17 Turedi et al. (2019)

Turedi et al. (2019) conducted a study to investigate the load-settlement and vertical stress analysis of ring footings on a loose sand bed. They used both laboratory model tests and numerical analyses, and performed a total of twenty tests. The ultimate capacities of the ring footings were determined using the finite element package Plaxis 3D, and the results were compared with theoretical results from the literature. The researchers examined the effects of ring width on the footing's bearing capacity and vertical stresses along the depth. They found that the experimental results were consistent with both the numerical and theoretical results. The circular footing shows the highest magnitude, decreasing as the ratio increases. Results from circular footings indicate a displacement intensification approximately 65% higher than those obtained from ring footings.

2.3.18 Vali et al. (2019)

Vali et al. (2019) investigated the effect of various loading position on bearing capacity of ring footing resting on both sandy and clayey soils using finite element limit analysis. They considered four different loading positions, namely, entire loading, inner loading, middle loading and outer loading. MC and Tresca yield surface have been used to predict the behavior of drained sand and undrained clayey soil respectively. Along with the loading positions, radius ratio, strength of soils was also varied. They concluded that the inner loading position has significant influence on bearing capacity for both soils. Also, failure patterns were drawn for all the cases and found that the failure patterns were same for all loading cases

2.3.19 Das et al (2021)

Das et al (2021) conducted numerical investigations to determine the ultimate bearing capacity of a ring footing on loose sand overlying dense sand. Lower and upper bound finite element limit analysis with second-order conic programming were employed to analyze various parameters, including the thickness and angle of internal friction of the top and bottom sand layers, as well as the radius ratio of the ring footing. The results showed that the bearing capacity ratio decreased with an increase in the thickness and friction angle of the dense sand layer. The presence of loose sand on top of the dense sand layer was found to negatively impact bearing capacity if not adequately analyzed. The bearing capacity ratio (BCR) also decreased with the increase in the thickness of the top loose sand layer, regardless of the radius ratio. For a given friction angle of both layers, the BCR decreased with an increase in the radius ratio until a specific value was reached, after which the BCR increased. The failure pattern observed in the study supported the results obtained for the BCR in various cases, which compared well with existing literature data.

2.3.20 Chavda and Dodagoudar (2021)

Chavda and Dodagoudar (2021) evaluated the bearing capacity factors of smooth and rough base ring footings, specifically N'_c, N'_q, and N'_γ, using FEM for a range of radius ratios (r_i/r_0) from 0 to 1. For radius ratios (r_i/r_0) between 0 and 0.98, axisymmetric formulation is used to compute the bearing capacity factors, whereas the plane strain formulation is used for radius ratio (r_i/r_0) = 1. The study investigates the impact of changes in the soil's Young's modulus and Poisson's ratio on the ring footing's ultimate bearing capacity. It also examines how the width of the ring footing affects N'_γ. An example problem with specified cohesion, surcharge, and unit weight is used to determine the pattern of variability in the ultimate bearing capacity of the ring footing for radius ratios (r_i/r_0) from 0 to 1. Based on this pattern, the study proposes an equation to estimate the ultimate bearing capacity of the ring footing using the ultimate bearing capacities of the circular and strip footings.

2.3.21 Hussein (2021)

Hussein (2021) presented a numerical analysis performed using PLAXIS software to calculate the bearing capacity factor N_γ for rough circular and ring footings on sand, based on Mohr-Coulomb's criterion for soil. The study examined the effects of various factors, such as angle of internal friction of sand (ϕ), radius ratio (n), and different external diameters of circular and ring footings. The load settlement curves for circular and ring footings are compared, with a focus on ultimate bearing capacity. The analysis revealed that the radius ratio has a significant impact on the ultimate bearing capacity of ring footings, which decreases with increasing radius ratio. The failure mode of ring footings is a general shear failure and has not affected by internal friction angle of sand. The lateral extent ratio (W/Do) decreases with increasing radius ratio for different internal friction angle of sand bed. The depth of failure surface (d/Do) under ring footings decreases with the increase of radius ratio for different internal friction angle.

2.4 LITERATURE REVIEW: ULTIMATE BEARING CAPACITY OF STRIP FOOTINGS ON UNSATURATED SOILS MECHANICS

Unsaturated soil mechanics is a relatively new field in contrast to the saturated soil mechanics. Although, the influence of matric suction on the growth of plants were long being studied in the field of agricultural science, but until the mid-half of the previous century not much studies were reported to induce the matric suction based-stability and settlement calculations in the design. The reason towards this reluctance was the lack of understanding and development of the unsaturated soil mechanics. Over the years, there have been notable advancements in understanding and modeling of unsaturated soils. One area of improvement in unsaturated mechanics is the development of experimental techniques and instrumentation. Researchers have worked on refining laboratory testing methods to accurately measure soil-water retention curves, which describe the relationship between soil suction and water content. Several SWRC-based models are prescribed which consider various factors such as suction, pore air pressure, and degree of saturation to accurately represent the stress-strain behavior of unsaturated soils. The following section consists of literature review of ultimate bearing capacity of strip footing resting on unsaturated soil.

2.4.1 Vanapalli and Mohamed (2007)

Vanapalli and Mohamed (2007) presented a simple approach to estimating the bearing capacity variation of unsaturated soil based on its matric suction. To accomplish this, they combined Terzaghi's conventional bearing capacity theory with matric suction. This approach was based on the same principles proposed by Vanapalli et al. (1996) to predict the shear strength of unsaturated soils. Using this technique, the bearing capacity of unsaturated soil can be predicted by utilizing the saturated shear strength parameters, c' and ϕ, and the soil-water retention curve. However, it is important to note that the variation of matric suction with respect to depth underneath the model footing is non-linear.

2.4.2 Oh and Vanapalli (2008)

Oh and Vanapalli (2008) provided a method for assessing bearing capacity and settlement by forecasting the stress versus settlement behaviour for unsaturated soil. In order to simulate stress versus settlement behaviour in unsaturated sandy soils, finite element analysis were also carried out. The results were found good agreement with measured and predicted settlements and bearing capacity. The importance of the air-entry value in determining bearing capacity, the accuracy of predictions when the effective internal friction angle were increased by 10%, and the usage of a different equation for estimating modulus of elasticity in the finite element analysis were highlighted. The study offered useful information for predicting stress vs settlement behaviour in unsaturated sandy soils overall.

2.4.3 Oh and Vanapalli (2013)

Oh and Vanapalli (2013) conducted a series footing tests in statically compacted unsaturated fine grained soils. Matric suction based modified effective-stress and total stress approaches were used to deduce the footing results and were validated with the in-situ plate load test results in unsaturated soils. The study concluded that plate load test findings in these soils can be reliably interpreted using the modified effective-stress approach. The testing soil was dried, ground up, and combined with distilled water. To comprehend differences in matric suction, the researchers created a soil-water characteristic curve. The study looked at specific failure scenarios and discovered that the estimation accuracy of various methods for bearing capacity varied. When employing conventional sample techniques, the modified total suction based method was thought to be the most plausible for calculating bearing capacity in unsaturated fine-grained soils.

2.4.4 Vanapalli and Mohamed (2013)

Vanapalli and Mohamed (2013) conducted a study on the bearing capacity and settlement behavior of surface and embedded model footings in unsaturated sands and investigated the effect of matric suction, overload stress, and dilation. The study compared predicted and measured values using modified versions of Terzaghi's equation and Schmertmann's CPT-based technique. The soil-water characteristic curve was created for poorly graded fine sand. There was good agreement between SWRC generated using other methods. The bearing capacity of unsaturated sands grew linearly with matric suction in the saturation zone, increased nonlinearly in the transition zone, and dropped in the residual zone. The study came to the conclusion that the modified Terzaghi's and modified Schmertmann's methods offered precise estimates of bearing capacity and settlement behaviour for sandy soils under both saturated and unsaturated circumstances.

2.4.5 Vo and Russell (2016)

Vo and Russell (2016) investigated the load-bearing capacity of strip footings on unsaturated soils by using effective stress basedslip line theory. The study found that both cohesion and suction had independent and similar effects on the effective stress in the governing equations. The non-uniform suction profile was found to have a significant influence on the load-bearing capacity. The depth to the groundwater table and footing width were also found important factors in determining the extent of suction's impact. These design charts given by them can be used to determine the bearing capacity for different combinations of factors and to evaluate changes resulting from seasonal variations in soil moisture.

2.4.6 Vahedifard and Robinson (2016)

Vahedifard and Robinson (2016) proposed a new analytical approach to estimate the ultimate bearing capacity of shallow foundations in variably saturated soils under steady flow. The proposed method incorporates a suction stress-based representation by using a closed-form equation to define the *suction stress characteristic curve* (SSCC) and the classic effective shear strength parameters and two fitting parameters to represent the SWRC. The study showed that different flow conditions can significantly affect the ultimate bearing capacity of clay, but different flow conditions have negligible effects on the ultimate bearing capacity of sand. The study also presented the ultimate bearing capacity profiles for various surface flux boundary conditions and depths of the water table.

2.4.7 Oh and Vanapalli (2017)

Oh and Vanapalli (2017) determined the bearing capacity of shallow foundations in unsaturated cohesive soils using Finite Element Analysis (FEA). The study included the estimate unsaturated soil parameters considering matric suction. The results showed good agreement between the values of the measured and anticipated bearing capacities. The study concluded that larger values of Poisson's ratio translate into better carrying capacity and have an impact on stress-settlement behaviour. The FEA with MTSA method were found to generate precise bearing capacity estimations as compared to other methodologies. The proposed FEA method offered a simple and practical tool for determining the bearing capacity of cohesive unsaturated soils.

2.4.8 Tang et al. (2017)

Tang et al. (2017) studied to predict the bearing capacity of shallow footings on unsaturated soil based on the effective stress principle. The authors presented equations that take into account the suction and the soil-water characteristic curve of the foundation soil as extra parameters for unsaturated soil. The validity of the equations was tested by comparing their predictions with published data from plate loading tests on unsaturated soils. The results showed that the predictions of the proposed equations were satisfactory, although there were uncertainties in the magnitude of the bearing capacity obtained experimentally.

2.4.9 Ghasemzadeh and Akbari (2019)

Ghasemzadeh and Akbari (2019) presented the limit equilibrium concept to predict the bearing capacity of unsaturated soil. The model considered non-linear variations of matric suction in the soil and also analyzed the bearing capacity with uniform and linear variations of soil suction. The model included the contribution of matric suction by introducing the apparent cohesion into the calculations, which arose from matric suction. The bearing capacity factor, N, due to matric suction, was calculated for different matric suction profiles, including uniform, linear, and nonlinear distributions. The model used the soil-water characteristic curve and soil properties under saturated conditions. The model was validated using both laboratory and field experimental data. The model was simple and could be useful for geotechnical engineers in designing foundations and earth structures to avoid high expenses.

2.4.10 Garakani et al. (2019)

Garakani et al. (2019) used two approaches to investigate the effect of degree of saturation and matric suction influence the ultimate bearing capacity of shallow foundations on unsaturated soils, particularly for fine-grained soils with low permeability: extending Vesic's solution for saturated soils by introducing a modification factor that considers the influence of matric suction on ultimate bearing capacity, and incorporating the unsaturated effective stress state and suction-dependent cohesion into a 3D finite-difference code. The results showed that the suction-dependent effective stress approach was a reliable method for predicting the load-displacement behavior of shallow foundations on unsaturated soils. The study emphasized the importance of considering the influence of matric suction on the ultimate bearing capacity of shallow foundations on unsaturated soils and provided useful analytical and numerical tools for predicting the load-displacement behavior of such foundations.

2.4.11 Anand and Sarkar (2020)

Anand and Sarkar (2020) studied focused on determining the bearing capacity of unsaturated fly ash deposits. In addition to the strength parameter, which had not been well studied, they emphasised the significance of taking into account variables like the infiltration rate ratio and the water retention characteristics curve (WRCC). To evaluate these factors' effects, nonlinear finite element analyses were carried out. The effects and uncertainties of these parameters on bearing capacity and settlement were assessed by the researchers using a probabilistic technique. To calculate bearing capacity and settlement while taking into account parameter fluctuations, prediction equations were created. The bearing capacity of strip footings resting on unsaturated fly ash deposits was calculated using Monte Carlo simulations. According to the study's findings, bearing capacity was considerably influenced by WRCC characteristics, infiltration rate, and variations in the groundwater table.

2.4.12 Du et al. (2020)

Du et al. (2010) conducted a parametric study using the discretization method of limit analysis to examine the bearing capacity of shallow foundations on unsaturated soils. They concentrated on concept of shear strength with respect to matric suction that varies with depth. The suction stress characteristic curve was created by the researchers to reflect changes in effective stress brought on by matric suction and soil saturation. The study provided bearing capacity graphs for various soil types, foundation widths, internal friction angles, air entry pressures, water table depths, soil unit weights, and surcharge loads through a parametric analysis. According to the findings, internal friction angle and foundation width had a beneficial affect on bearing capacity, however sand had little of an impact.

2.4.13 Yan et al. (2020)

Yan et al. (2020) discussed a new formulation for bearing capacity of footing that takes into account the effect of intermediate principal stress. They showed that matric suction and its profiles can significantly enhance the ultimate bearing capacity of strip foundations in unsaturated soils. The effect of strength nonlinearity was also investigated, with two methods compared. Method I used a small and stable value of the angle ϕ^b has simple calculation steps whereas Method II used with a hyperbolic function of the angle $\phi_{b.}$ Method I was very simple as compared to method II, but the results of Method II was found more consistent with practical conditions.

2.4.14 Afsharpour et al. (2022)

Afsharpour et al. (2022) evaluated ultimate bearing capacity of shallow foundations on partially saturated soils under a wide range of combined vertical-horizontal-moment loadings using the well-established limit equilibrium method and the unified effective stress approach. The bearing capacity was determined by solving four equilibrium equations, which consider Coulomb failure mechanism, Bishop effective stress concept, and a linear variation of the induced matric suction beneath the foundation. The general failure loci of shallow foundations resting on unsaturated soils under different hydraulic conditions were presented in *V-H-M* spaces. The study demonstrated that the matric suction has a significant impact on the bearing capacity of shallow foundations. The effect of induced suction on the ultimate bearing capacity of obliquely-loaded foundations was found more pronounced than that of eccentrically-loaded footings.

2.4.15 Anand and Sarkar (2022)

Anand and Sarkar (2022) presented a comprehensive study on the seismic bearing capacity of shallow strip footings in unsaturated fly ash deposits. A novel strategy that was applied which included the strength nonlinearity of unsaturated soil. The study developed a closed-form formulation for the permissible bearing capacity and validated it using finite element limit analysis. They investigated the effect of different characteristics, such as the surface flux boundary condition, water table depth, and seismic acceleration coefficient, on bearing capacity. The bearing capacity was reduced by up to 48% when the flux situation shifts from a hydrostatic (no flow) condition to a saturated flow condition The risk of footing failure was found to be varying from 25 to 85% for the range of infiltration rate ratios.

2.4.16 Fathipour et al. (2022)

Fathipour et al. (2022) investigated the bearing capacity of strip footings on unsaturated soils that are under combined loading using the lower-bound limit analysis with the finite element discretization combined with second-order cone programming (SOCP) and soil was modelled as universal Mohr-Coulomb yield criterion. To account for the matric suction induced below the surface footing, the suction stress concept was adopted under no-flow and steady-state infiltration/evaporation flow conditions. To verify the model, the results obtained from the lower-bound finite element limit analysis were compared with several previous studies in the literature. They discussed the substantial contribution of suction stress to the evolution of failure loci and the distribution of subsurface stresses for the shallow foundation under inclined and eccentric loadings.

2.4.17 Tan and Vanapalli (2023)

Tan and Vanapalli (2023) proposed a slip line method combined with analytical solutions to assess the bearing capacity of foundations under inclined or eccentric loading and unsaturated flow conditions. The proposed method was found to provide reliable results, and the study concluded that inclination angle and eccentricity had negative effects on the vertical loading components, while horizontal loading components increased and then decreased with increasing inclination angle and eccentricity ratio, respectively. The failure envelopes expanded under evaporation and shrunk under infiltration, with longer infiltration duration resulting in envelope shrinkage.

2.4.18 Yilmazoglu and Ozocak (2023)

Yilmazoglu and Ozocak (2023) conducted direct shear box test on unsaturated silt to determine ultimate bearing capacity of different types and sizes of model foundations placed on silty soil layers with varying degrees of soil saturation and void ratio values. A new equation was proposed for determining ultimate bearing capacity of unsaturated soils based on unconfined compressive strength tests, degree of saturation, and fitting parameter. The study provided solutions values for the design of shallow foundations on unsaturated silty soils. The solution given in this study follows the trends provided by previous authors. The bearing capacity factors of unsaturated are more than that of saturated.

2.4.19 Roy and Chakraborty (2023)

Roy and Chakraborty (2023) developed a upper bound rigid-block method for determining the bearing capacity of shallow strip foundations on unsaturated soil by introducing an additional bearing capacity factor that considered matric suction in variably saturated soils. The authors conducted an extensive study to investigate the impact of various factors like soil strength, footing-soil interface condition, fluid flow, and water table fluctuations on the suction-induced load-carrying capacity, and their results were consistent with previous research. A parametric study has been done and found that bearing capacity increases with suction matric.

2.5 RESEARCH GAP AND OBJECTIVES OF THE PRESENT THESIS

The literature reviews on the development of the limit analysis clearly suggests that the usage of FELA tool for solving the axisymmetric geotechnical stability problems are relatively limited in comparison to the plane-strain geo-structures. Ring footing is a widely used axisymmetric substructure for supporting various off-shore and on-shore superstructures. Ring footing can withstand heavy loads and is more economical as it decreases the amount of construction material and the cost thereof. While the previous research has shed light on the behavior of ring footings on homogeneous soils, the influence of soil heterogeneity on bearing capacity remains relatively unexplored. The conventional way of depositional processes leads to the development of stratified soils. Understanding the behavior of ring footings on these layered soils is crucial for accurate foundation design and construction. Furthermore, most existing studies on ring footings assume uniform distribution of vertical loading across the entire footing surface. However, there are cases where the vertical load is applied partially over the annular section of the footing. Nonetheless, there is a dearth of comprehensive research that thoroughly investigates the bearing capacity of ring footings on two-layered soils while considering the effect of different loading positions. Ring footings are also constructed over rocks. However, there is hardly any analysis available in the literature that rigorously assessed the behaviour of ring footing resting on rock mass and subjected to partial loading.

Considering these research gaps, the first broad objective is to devise a rigorous LB-FELA nonlinear formulation and to adequately verify the formulation. The shape of the yield surfaces creates a problem in this regard. All the chosen yield criteria (Mohr-Coulomb, Tresca, and Hoek-Brown) exhibit sharp discontinuities. During the computational process, constructing the gradient vectors and the Hessian matrices with the usage of the original yield criterion (having sharp corners) becomes problematic. Hence, following Sloan and Booker (1986), Abbo and Sloan (1995), and Abbo et al. (2011), the yield criteria are to be smoothened by using the hyperbolic approximation in the meridian plane and the trigonometric round-off technique in the octahedral plane. Thereafter, with the help of the LB-FELA formulations, the following problems are to be addressed:

a) Bearing capacity of ring footing resting on sandy-clayey soil.
b) Bearing capacity of ring footing resting on two layered soil due to various load position.
c) Bearing capacity of ring footing resting on rockmass due to various load position.

Most of the studies on bearing capacity primarily consider the soil to be completely saturated or completely dry. However, it is important to note that shallow foundations are typically built near the ground surface, above the water table where the soil is often unsaturated. Failing to account for the influence of matric suction within the unsaturated soils can lead to inaccurate estimations of the bearing capacity of shallow foundations. However, to date, there is a lack of research in finding the bearing capacity of shallow foundations resting on unsaturated soils by using the numerical limit analysis. Implementing unsaturated soil mechanics equips engineers with a more comprehensive and accurate framework for geotechnical analyses and design processes, accommodating a broader spectrum of soil conditions.

This research gap motivates the next objective- to develop a rigorous UB-FELA formulation by duly considering the variation of suction above the groundwater table. The formulation needs to be flexible enough so that it can incorporate the unsaturated soil properties, the effect of the groundwater table fluctuation, and the climatic changes (infiltration /evaporation). The external influences (e.g. rainfall) also cause time-dependent variation in the matric suction profiles; this temporal impact also need to be induced into the formulation. By using the proposed UB-FELA methodology the following problems are chosen to be solved.

a) Bearing capacity of strip footing resting homogenous unsaturated sandy soil.

b) Bearing capacity of strip footing resting homogenous unsaturated sandy soil under combined load.

c) Bearing capacity of strip footing resting homogenous unsaturated sandy soil under transient flow.

It is envisaged that the findings of this study in the form of design charts will contribute to the existing body of knowledge, and provide insights and offer practical recommendations for foundation design guidelines to the design engineers.

2.5 Summary

The present chapter presents existing research works on limit analysis, ring foundations, and the unsaturated bearing capacity of strip footing. The first section highlights the development of limit analysis for upper and lower bound limit analysis by improving mathematical optimization methods. The evolution of limit analysis from 2D to 3D models has significantly enhanced the ability of engineers to analyze soil structures more accurately and efficiently. However, considering the vastness of geotechnical structures and the variability in the properties of geomaterials, there are many problems yet to have a rigorous solution. Some of those problems concerning the ring foundations are identified and examined in the subsequent chapters. In the following section, the articles focusing on the estimation of the bearing capacity of strip footings on unsaturated soils are elucidated. The improvement of unsaturated mechanics in geotechnical engineering has led to more reliable predictions of soil behavior and realistic design approaches. However, the development of unsaturated soil mechanics is phenomenological in nature and mostly restricted within the academic community. Very few real-life projects integrate the theoretical findings of the vadose zone-influenced stability and settlement analysis in the design calculations. The design charts considering the effect of matric suction are not readily available. The contributions of the subsequent chapters aim to fill some of these research gaps.