CHAPTER 2

Literature Review

2.1 INTRODUCTION

This chapter provides a concise overview of the literature from two perspectives: (a) Consolidation theories in saturated soil mechanics and various modifications to the conventional theory, encompassing non-uniform distribution of pore water pressure, layered soil, variations in permeability and compressibility, non-Darcian flow, time-dependent loading, and coupled consolidation theory to enhance its applicability in field analysis. (b) A review of the significance of unsaturated soil consolidation and modifications .

2.2 LITERATURES ON SATURATED CONSOLIDATION

2.2.1 Theories

Terzaghi (1925) introduced the concept of one-dimensional consolidation by assuming that soil particles are bound together by molecular forces, creating a porous material with elastic properties. When a load is applied, settlement occurs based on the rate of water expulsion from voids. Initially, Terzaghi's theory addressed settlement under a constant load, limiting lateral expansion. However, it was later expanded to three dimensions and applicable to variable loads over time. In Terzaghi's model, the soil is assumed to be laterally confined, with strains occurring only vertically. The conventional theory of consolidation, as formulated by Terzaghi (1925), assumes that only the excess pore pressure contributes to the progression of consolidation. This aligns with the assumption of one-dimensional strain. The one-dimensional nature of consolidation arises either from lateral physical restraint, as seen in the oedometer test, or from surface loading that is uniform in magnitude and extends infinitely in all directions. Despite its apparent versatility, the one-dimensional theory has significant drawbacks. The most serious is its reliance on a single vertical component of displacement, necessitating separate analyses for settlement magnitude and settlement progress. Since these two phenomena are inherently coupled, any separation is merely an ad hoc measure. Another interpretation of the conventional theory, proposed by Rendulic in 1936, suggests that the time behavior of internal total stresses is strictly equivalent to that of the applied total stresses. In other words, the internal volumetric components of total stress are assumed to exhibit the same time history as the applied volumetric stress components. This interpretation has led to the development of the Terzaghi-Rendulic (pseudo three-dimensional) theory. The pseudo three-dimensional theory represents a middle ground between the one-dimensional theory and a true three-dimensional theory. Although this theory is more complex than the one-dimensional theory, its versatility is somewhat limited. Additionally, the pseudo three-dimensional theory still fails to couple the magnitude and progress of settlement. Moreover, certain effects characteristic of three-dimensional consolidation (Gibson, Knight, and Taylor, 1963; Josselin De Jong, 1963b; Schiffman, 1965a, 1965b; Verruijt, 1965) do not appear in the pseudo theory. The theory of three-dimensional primary consolidation, or poroelasticity, was first formulated by Biot in 1941. This three-dimensional consolidation theory provides a coupling between the magnitude and progress of displacement without requiring special assumptions about time-dependent variables. In this theory, there are four such variables: the three displacement components and the excess pore pressure. The state of total stress is a function of the excess pore pressure and the constitutive relationships of the soil skeleton. This theory is completely self-consistent and does not necessitate the separation of magnitude and progress of settlement; instead, they are interdependent aspects of a single phenomenon.

2.2.2 Non-uniform initial excess pore water pressure

2.2.2.1 Singh (2005)

Analytical solutions for one-dimensional transient consolidation under triangular loadings of pore-water pressure are presented, considering both basic and reverse triangular loadings. The diagnostic curve method involves matching plotted points with a master diagnostic curve, while the peak derivative method requires locating the peak of a unimodal curve. Additionally, the peak derivative method can identify nonideal conditions and validate the estimated parameters. These proposed methods provide reliably accurate estimates for the data and error magnitudes considered.

2.2.2.2 Singh (2008)

Analytical solutions for pore-water pressure distribution and transient consolidation settlement under linear loading with one-way drainage have been obtained. Diagnostic curve methods have been proposed for simultaneously estimating the consolidation coefficient, final settlement, and the ratio of excess pore-water pressures at the top and bottom of the clay layer from observed settlements under linear loading of pore-water pressure with one-way drainage.

2.2.2.3 Singh and Swamee (2008)

Simple yet accurate, invertible approximations of consolidation curves have been developed for triangular loadings of pore-water pressure. These approximations enable the easy calculation of the degree of consolidation corresponding to a time factor or the time factor corresponding to a degree of consolidation, which would be beneficial for engineering applications. Additionally, explicit equations for estimating the consolidation coefficient and final settlement from two settlement readings have been proposed using these approximations.

2.2.2.4 Lovisa et al. (2010)

This paper investigates the consolidation behaviour of a soil stratum subjected to six different initial excess pore pressure distributions under one-dimensional loading. Revisiting the six cases of standard initial excess pore pressure distributions discussed in the literature reveals that the term "degree of consolidation" alone is inadequate for fully describing the consolidation process. Therefore, for a complete description of consolidation behaviour, it is recommended to view the degree of consolidation isochrones alongside pore pressure isochrones, which exhibit significantly different shapes. The investigation into the effects of asymmetric initial pore pressure distributions revealed a phenomenon of pressure redistribution during consolidation. When the majority of initial excess pore pressure is concentrated in one region, there is a redistribution of excess pore pressures toward the region of minimal pore pressure during the initial stages of consolidation, resulting in the pore pressure exceeding the initial value.

2.2.2.5 Lovisa et al. (2012)

In this paper, several symmetric and asymmetric initial excess pore pressure distributions are examined using a series solution method. Excess pore pressure isochrones and average degree of consolidation plots are generated for all cases, assuming an impervious boundary at the base of the clay stratum. These plots allow users to determine the average degree of consolidation and pore pressure at specific depths for various loading scenarios. The study also finds that pore pressure redistribution is notably more prevalent in singly drained clays, where pore-water pressures at certain depths can increase at specific times—a phenomenon not typically anticipated during consolidation.

2.2.2.6 Lovisa and sivakugan (2014)

Two methods have been proposed to determine the average degree of consolidation for a layer (either singly or doubly drained) subjected to a non-uniform initial excess pore water pressure distribution (u_0-distribution). The first, more comprehensive method involves implementing a generalized semi-analytical solution to Terzaghi's one-dimensional consolidation equation using *MATLAB*. The second, simpler method requires only basic knowledge of the shape of the u_0-distribution and access to widely available percentage consolidation versus time factor (U–T) values for a uniform initial excess pore pressure distribution.

2.2.2.7 Zhang et al (2015)

The study investigates the effects of initial excess pore pressure distributions, depth-dependent additional stress, and loading modes on the consolidation process of the soft foundation with an upper crust. Results indicate that the distributions of initial excess pore pressure and additional stress, along with loading rates, significantly influence consolidation. This influence is more pronounced under single-drained conditions compared to double-drained conditions. Furthermore, compared to uniform distributions, decreasing distributions of initial pore pressure and additional stress with depth accelerate consolidation during the earlier and middle stages. Additionally, higher loading rates lead to faster consolidation of the soft foundation with an upper crust.

2.2.3 Layered Soil

2.2.3.1 Chen et al. (2005)

The current article represents applying the differential quadrature method (DQM) for analysing the one-dimensional nonlinear consolidation of multi-layered soil under partially drained boundaries and arbitrary loading conditions. It considers the influence of initial effective stress distribution. The research demonstrates the accuracy of DQM. Moreover, due to its uniform matrix structure, DQM offers ease of programming and enables the consideration of various complex factors in the consolidation problem.

2.2.3.2 Mion et al. (2010)

This paper delves into the analytical solution of the one-dimensional consolidation for a two-layered soil by considering the multi-level loading conditions. The analytical solution comprises two components: a general consolidation solution applicable to both single-drainage and double drainage boundary. The average degree of consolidation is computed for each loading stage, providing insights into the consolidation response of a two-layered profile.

2.2.3.3 Kim and Mission (2011)

This study derives interface boundary relations for the numerical analysis of one-dimensional consolidation in multilayered clay profiles. Finite difference solutions are formulated using Mikasa's consolidation equation, which assumes infinitesimal strains and constant consolidation parameters, similar to the classic Terzaghi equation. Numerical examples are provided for multilayer clay profiles under single and double drainage boundary conditions, validating predicted excess pore pressures, strains, settlements, and rates of consolidation. These interface boundary relations express infinitesimal strains equivalently to excess pore pressures, facilitating accurate numerical predictions.

2.2.3.4 Zhang et al. (2015)

This study presents a model for the one-dimensional consolidation of a two-layered soil, non-uniform initial excess pore pressure and additional stress, for time-dependent loading under different drainage conditions. The study derives a general analytical solution and applies it for analysing special cases such as single-drained and double-drained conditions under instantaneous and uniform loading.

2.2.3.5 Yang et al. (2021)

The study begins by establishing governing equations for the one-dimensional consolidation problem of layered soils under a ramp load. Subsequently, an analytical solution for excess pore water pressure and average consolidation degree is derived using Laplace transform and matrix transfer methods. When the parameters of both the layers are equal, the excess pore water pressure in a single-layered soil exhibits symmetric distribution along the depth, with the plane of maximum excess pore water pressure positioned at the soil's midpoint. Conversely, when the parameters are unequal, the distribution becomes asymmetric, with the plane of maximum excess pore water pressure closer to the boundary with the smaller interface parameter. The stratification of layered soil significantly influences the distribution of excess pore water pressure along the depth.

2.2.4 Varying permeability and compressibility

2.2.4.1 Schiffman (1958)

The theory of variable permeability is extensively developed with specific solutions, addressing the consolidation of a doubly-drained layer of clay soil under two- and three-dimensional loading. Extensions to variable permeability problems are suggested.The exact solution for consolidation under constant load but variable permeability is presented, alongside constant permeability solutions considering a perfect drain without smear. For cases involving linear construction loading and the presence of a smear zone, constant permeability solutions are also provided.

2.2.4.2 Xie et al. (1995)

This paper introduces an analytical solution for the one-dimensional consolidation of soft soil. The solution is based on assumptions proposed by Davis and Raymond (1965), which state that the decrease in permeability is proportional to the decrease in compressibility during the soil consolidation process and that the initial effective stress distribution remains constant with depth. In nonlinear consolidation, there exists a distinction between U_p and U_s. Furthermore, U_p slightly surpasses U_s concurrently.

2.2.4.3 Lekha et al. 2003

The analytical solution provided in this study incorporates linear responses in e – log *k* and *e* – log *p'*, accounting for instantaneous loading effects. By considering C_c as the slope of the *e* – log *p'* line and *M* as the slope of the *e* – log *k* line, a parameter C_c/M is identified, which governs the consolidation rate. This paper presents an analytical closed-form solution for vertical consolidation, considering variations in compressibility and permeability. A key parameter, C_c/M, reflecting the nonlinearity in compressibility and permeability behaviors, is identified and shown to substantially influence the rate of the consolidation process.

2.2.4.4 Zhuang et al. (2005)

This paper presents a generalized theory for one dimensional consolidation of saturated soft clay with variable compressibility and permeability. The semi-analytical solution presented here takes into account the well known empiricale-logk and *e-log p'* relations under instantaneous loading. Study of the consolidation behaviors showed that the ratio of C_c and*M* govern the ratio of consolidation. A simulative laboratory investigation with GDS advanced consolidation system was made to analyze the clay consolidation process and compare the results with the semi-analytical solution.

2.2.4.5 Ying-chun et al. (2005)

This paper introduces a comprehensive theory for one-dimensional consolidation of saturated soft clay, incorporating variable compressibility and permeability. Examination of consolidation behaviors revealed that the ratio of C_c to *M* influences the consolidation ratio. A laboratory investigation using the GDS advanced consolidation system was conducted to analyze the clay consolidation process and to compare the findings with the semi-analytical solution. The semi-analytical solution proves to be highly effective for addressing complex consolidation problems involving varied compressibility and permeability.

2.2.4.6 Abbasi et al. (2007)

This paper introduces a one-dimensional nonlinear partial differential equation to forecast consolidation characteristics of soft clays, incorporating variable values for C_v. The solution employs a finite difference method to address the developed nonlinear equation. The coefficient of consolidation undergoes variations due to changes in permeability and volume compressibility coefficients, which occur as effective stress changes throughout the consolidation process. Two coefficients (C_n and α) are introduced to characterize the changes in the coefficient of consolidation concerning effective stress, thereby accounting for alterations in the coefficients of volume compressibility and permeability during consolidation.

2.2.4.7 Toufigh and Ouria (2009)

This study extends Olson's solution for one-dimensional consolidation under considering varying coefficients of consolidation dependent on the loading. To establish the relationship between the coefficient of consolidation and the time of corresponding pressure applied on the specimens for each loading rate test, falling head permeability tests are explicitly conducted at various stages during the conventional consolidation tests. Subsequently, the hereditary integral of viscoelastic theory is employed to predict the settlement curve with time for each loading rate test. The study reveals that the theoretical predictions utilizing loading-dependent coefficients of consolidation align well with experimental results in terms of consolidation settlement.

2.2.5 Non darcian flow

2.2.5.1 Elnaggar et al. (1973)

The study investigates the impact of non-Darcian flow on the consolidation behavior of clay soils and evaluates its significance in extrapolating laboratory findings to field scenarios. This is achieved by proposing a reasonably general four-parameter velocity-gradient relationship, capable of characterizing a substantial portion of existing experimental data. This relationship is then integrated with classical consolidation theory's standard assumptions to formulate a nonlinear parabolic partial differential equation, solved using a finite difference technique. Empirical extensions of stability and convergence criteria from related linear and quasi-linear equations to the associated nonlinear equations are provided.

2.2.5.2 Ing and Xiaoyan (2002)

The present article involved solving highly nonlinear continuity equations numerically using an approximate method. Incorporating the non-Darcian flow, characterized by the threshold gradient i_l and exponent m, into the coupled consolidation theory was a focus of the paper. A dedicated program was developed based on these equations, and finite element formulations were outlined. Additionally, the impact of non-Darcian flow on consolidation was investigated.

2.2.5.3 Zhao and Gong (2019)

This paper establishes the governing equation for one-dimensional nonlinear large strain consolidation, incorporating non-Darcian flow effects. The equation considers various factors such as vertical strain, soil self-weight, geometric nonlinearity, continuity of pore water flow, relative velocity of fluid and solid phases, and changing compressibility and hydraulic conductivity during consolidation. A numerical solution is then obtained using the finite difference method (FDM), which is verified to exhibit excellent accuracy.

Results indicate that increasing the non-Darcian exponent initially accelerates consolidation rates but eventually slows them down. However, it does not affect the final settlement of the soil layer.

2.2.5.4 Zong et al. (2021)

This study addresses the one-dimensional consolidation problem of soft soil under self-weight and non-Darcian flow conditions by incorporating a continuous drainage boundary. A numerical solution is developed using the finite difference method and its accuracy is verified by comparison with existing analytical and numerical solutions. Leveraging this solution, the consolidation behavior of the soil is thoroughly analyzed by adjusting various parameters. The findings indicates that soil consolidation solutions considering non-Darcian flow, the consolidation rate with Darcy flow is observed to be faster.

2.2.6 Time dependent loading

2.2.6.1 Schiffman (1958)

The application of consolidation theory often faces limitations due to inherent working conditions. This paper expands the theory by incorporating variations in loading rate and coefficient of permeability during consolidation. By including these additional conditions, the fundamental differential equation is generalized to its most comprehensive form. Although the resulting equation is nonlinear, an exponential approximation is devised to linearize it, facilitating the solution of the consolidation boundary value problem. Detailed treatment is provided for the one-dimensional consolidation problem concerning a layer of clay soil sandwiched between two sand layers. A comprehensive solution is offered for constant permeability and arbitrary loading rates. Specific solutions are outlined for consolidation during linear construction periods, enabling practical time computations.

2.2.6.2 Wilson and Elgohary (1974)

A theoretical approach is employed to model the consolidation process of a saturated soil layer experiencing cyclic loading. The consolidation, advancing from the drainage boundary inward, occurs at a slower rate compared to consolidation under continuous loading of equivalent magnitude. This deceleration is attributed to the development of positive and negative pore-water pressures during loading and unloading cycles, resulting in water flow into and out of the soil. Ultimately, an equilibrium consolidation ratio is attained, which varies depending on the cyclic loading pattern. Complete consolidation to 100% is unattainable under cyclic loading conditions.

2.2.6.3 Baligh and Levadoux (1978)

This article introduces a theoretical framework for one-dimensional consolidation of an inelastic normally consolidated clay layer under cyclic loading. Theoretical solutions are provided to forecast the excess pore pressures and settlements that reach a steady state after numerous cycles. Additionally, approximate solutions offer both upper and lower bounds for settlement over time. Finite difference solutions corroborate the theoretical analyses and offer valuable insights, particularly for scenarios involving rapid cyclic loading. Practical applications of the prediction method are demonstrated through design charts and an illustrative example.

2.2.6.4 Xie and Pan (1995)

This study reveal the impact of various cyclic loading patterns, including trapezoidal cyclic loading. Utilizing the assumptions proposed by Davis and Raymond (1965), which state that the reduction in permeability is proportionate to the decrease in compressibility during soil consolidation, and that the initial effective stress remains constant with depth, an analytical solution is derived for the one-dimensional nonlinear consolidation of soil subjected to trapezoidal cyclic loading. In comparison to constant and linear loading conditions, under cyclic loading, U_s, U_p, and effective stress σ' do not exhibit continuous increases over time; instead, they fluctuate with loading and unloading. Initially, these differences are minimal. Following the initial unloading, the disparity gradually amplifies. Consequently, the average consolidation degrees of soil under cyclic loading significantly lag behind those under constant and linear loading with identical maximum loading.

2.2.6.5 Conte and Troncone (2006)

This paper introduces an analytical solution for analyzing the one-dimensional consolidation of saturated soil layers under general time-dependent loading conditions. A practical calculation method utilizing Fourier series is proposed, allowing consideration of both single loads and cyclic loads by selecting an appropriate period. Several comparisons with existing theoretical solutions are provided to evaluate the accuracy of the proposed procedure. Furthermore, experimental results from oedometer tests conducted in this study and from a well-documented case history involving a large embankment constructed on compressible soils are analyzed using this solution. This analysis serves to assess the coefficient of consolidation of the soil.

2.2.6.6 Herrmann and Gendy (2014)

This paper introduces the Layer Equation Method (LEM) as an approach for analyzing time-dependent settlement problems, particularly in scenarios involving deep excavations for structures with basements. Unlike many existing meshless methods, LEM offers a semi-analytical solution that involves deriving a limited number of algebraic equations instead of numerically solving partial differential equations. This results in a significant reduction in problem variables. The LEM technique can accommodate variable initial stress along clay layers and is adaptable to stress coefficient techniques, allowing consideration of vertical stress at any node within the soil. An application of the method to the reloading time-dependent settlement of clay is presented, addressing scenarios where soil stress decreases due to excavation and subsequent reloading of the soil becomes a crucial consideration.

2.2.6.7 Chai et al. (2022)

Drawing from theoretical analysis and finite element simulations, a straightforward approach for calculating one-dimensional (1D) consolidation settlement induced by intermittent cyclic loads has been introduced. For such loads characterized by a period, loading time increment , and a maximum load , the consolidation-induced compression can generally be assessed similarly to that caused by a static load. Furthermore, it is suggested that the total settlement comprises both consolidation and creep deformations. In conclusion, the proposed method offers a valuable design tool for estimating the consolidation impact of intermittent cyclic loads.

2.2.6.8 Satwik and Chakraborty (2022)

This paper aims to investigate the effects of cyclic loading on the one-dimensional consolidation of soft clays subjected to non-Darcian fluid flow. Three types of cyclic loading patterns—trapezoidal, triangular, and haversine—are examined, both with and without rest periods. The analyses employ the fully implicit scheme of the finite difference method. Hydraulic boundary conditions are classified as pervious or impervious. To assess the influence of flow law on cyclic-load-induced consolidation, curves are plotted for specific spatial points and the entire layer. These curves demonstrate notable deviations between Darcian and non-Darcian flow, particularly after reaching a steady state. The paper also identifies a critical rest period where the chosen flow law significantly impacts elastic rebound.

2.2.7 Coupled consolidation

2.2.7.1 Lewis et al. (1991)

This study thoroughly examines the coupling and uncoupling dynamics between equilibrium and mass balance equations in soil consolidation problems. A method for assessing the degree of coupling strength is outlined. Special attention is placed on subsidence issues, where the coupled nature of the problem is occasionally doubted. The analysis demonstrates that even in scenarios involving a single pumped aquifer, most situations exhibit coupling effects.

2.2.7.2 Huang et al. (2010)

The study combines Coupled Biot consolidation theory with the random finite-element method to examine the consolidation behavior of soil deposits with spatially variable properties in both one-dimensional (1D) and two-dimensional (2D) spaces. The coefficient of volume compressibility (m_v) and soil permeability (k) are considered as lognormally distributed random variables. The random fields of m_v and k are generated using the local average subdivision method, accounting for spatial correlation, local averaging, and cross correlations. These generated random variables are then mapped onto a finite-element mesh, followed by Monte Carlo finite-element simulations. Parametric studies are conducted to investigate the impact of standard deviation, spatial correlation length, and cross-correlation coefficient on output statistics related to the overall "equivalent" coefficient of consolidation. The study highlights that the average degree of consolidation, defined by excess pore pressure and settlement, differs in heterogeneous soils. Additionally, the dimensional effect on soil consolidation behaviors is explored by comparing the results between 1D and 2D scenarios.

2.2.7.3 Osman (2010)

It is demonstrated in the present article that both the uncoupled analysis and the coupled analysis give the same governing equation for pore fluid pressure dissipation with time. A simplified procedure for deriving transient strain components is illustrated. A general solution for time-dependent displacements is obtained using uncoupled consolidation analysis. Close agreement is evident between the new approximate uncoupled analysis solution and the existing coupled analysis solution with a maximum error of less than 0.5 %.

2.2.7.4 Deng et al. (2016)

A nonlinear flow relationship, accounting for fluid flow in the soil skeleton following Hansbo's non-Darcian flow and considering changes in the coefficient of permeability with void ratio, was integrated into Biot's general consolidation theory. This facilitated the simulation of consolidation in normally consolidated soft ground, with or without vertical drains. The governing equations incorporating the coupled nonlinear flow model were initially presented for force equilibrium conditions and subsequently for continuity conditions. Using the weighted residual method, finite element (FE) formulations were derived, and an existing FE program was modified to accommodate the nonlinear flow model. Comparative analyses were conducted, involving established theoretical solutions and numerical solutions, yielding satisfactory results. Building upon this foundation, the effect of coupled nonlinear flow on consolidation development was investigated.

2.2.7.5 Baqersad et al. (2016)

This paper examines the consolidation settlement of a strip footing placed on a finite layer of saturated soil using the finite element method. Biot's coupled consolidation equations, which simultaneously determine soil deformation and excess pore pressure in each time step, reflecting hydro-mechanical coupling, are utilized. By assuming constant total stress over time and considering volume strain as a function of isotropic effective stress, uncoupled consolidation equations are derived from the coupled equations. In these uncoupled equations, excess pore pressure and deformation are determined separately. This approach allows for the identification of excess pore pressure in the initial stage, followed by the determination of soil deformation through effective stress-strain analyses.

2.3 LITERATURE ON UNSATURATED CONSOLIDATION

2.3.1 Theories

Biot introduced a consolidation theory for unsaturated soil for occluded air bubbles. two constitutive equations associated with stress and strain were developed in terms of effective stress (σ-u_w) and pore-water pressure (u_w) separately. This approach acknowledged the necessity of the difference between total stress and pore-water pressure effects. One of the consecutive equations correlated the void ratio with the stress state, while the other related water content to the stress state. For one-dimensional consolidation Biot's theory have the same equation as Terzaghi’s, however, c_v was modified to take into account the compressibility of the pore fluid.

Fredlund and Hasan (1979) presented two partial differential equations (PDEs) to analyze the flow of excess pore air and excess pore water during soil consolidation in unsaturated conditions. It is assumed that the air phase and the water phase were continuous. Darcy’s law and Fick’s law were employed to describe the flow of water and air, respectively. It is considered that the coefficients of permeability of water and air were functions of matric suction or soil volume-mass properties. Both equations were solved simultaneously, and the method is commonly referred to as a two-phase flow approach.

2.3.2 Non-uniform initial excess pore pressures

2.3.2.1 Zhou and Zhao (2014)

The paper provides analytical solutions for various loading scenarios (instantaneous, ramp, exponential) and drainage conditions, along with tables for practical engineering applications. Case studies demonstrate good agreement with existing analytical solutions and explore consolidation behaviours of unsaturated soils, including the average degree of consolidation under different loading patterns and drainage conditions. Additionally, pore-water pressure isochrones for various initial pore pressure distributions and drainage conditions are presented and discussed. This paper introduces a straightforward analytical solution to Fredlund and Hasan's one-dimensional consolidation theory for unsaturated soils. It assumes constant coefficients of permeability and volume change throughout the consolidation process. By introducing two new variables, the coupled governing equations of pore-water and pore-air pressures are transformed into a simpler set of partial differential equations, readily solvable using standard mathematical formulas.

2.3.2.2 Zhao et al. 2014

This study examines the one-dimensional consolidation of unsaturated soil under time-dependent loading, utilizing the 1D consolidation theories of unsaturated soil. The approach employs the differential quadrature method (DQM) to generate a comprehensive solution, accommodating diverse boundary conditions, initial pore-water and pore-air distributions, and intricate time-dependent loading scenarios. Results demonstrate that the DQM solution yields higher accuracy compared to the finite-difference method with minimal sampling points. Furthermore, the general solution circumvents the need for laborious computations involved in solving eigenequations inherent in analytical solutions. Moreover, the proposed solution proves more practical for engineering applications due to its versatility in addressing complex initial, boundary, and loading conditions.

2.3.3 Impeded boundary conditions

2.3.3.1 Wang et al. (2017a)

In the present study one-dimensional (1D) consolidation equations are solved by introducing two variables to transform the coupled governing equations into a set of partial differential equations. The study illustrates changes in pore-air and pore-water pressures, as well as soil settlement, over time, considering different semi-permeable drainage boundary parameters. Parametric studies further investigate pressure variations with respect to the ratio of air permeability coefficient to water permeability coefficient and depth.

2.3.3.2 Wang et al. (2017b)

In this study, semi-analytical solutions for 1D consolidation equations in unsaturated soils with semi-permeable drainage boundaries under time-dependent loadings were derived using two related variables, ϕ_1 and ϕ_2, along with the Laplace transform. A higher ratio of air-to-water permeability coefficient (k_a/k_w) accelerates pore-air pressure dissipation at later stages, while changes in pore-water pressure occur mainly at intermediate stages across different k_a/k_w values.

2.3.3.3 Wang et al. (2017c)

The study presented in this paper derives semi-analytical solutions for the one-dimensional consolidation equation in unsaturated soils with symmetric semi-permeable drainage boundaries, utilizing two related variables and the Laplace transform technique. The semi-analytical solutions proposed in this study offer greater generality compared to previous solutions found in the literature. Higher values of R_T and R_B result in quicker pore pressure dissipation. When R_T or R_B exceeds 100, the dissipation patterns of pore pressures remain unchanged, indicating permeable drainage boundary conditions.

2.3.3.4 Zhao et at. (2020)

This study introduces a novel explicit analytical solution for the one-dimensional consolidation of unsaturated soil with a semi-permeable boundary. By assuming two independent stress variables and utilizing the governing equations proposed by Fredlund, the eigenfunction expansion method is employed to formulate an explicit analytical solution for computing excess pore-water and pore-air pressures in unsaturated soil under external loads. In comparison to the referenced semi-analytical solution, the present developed analytical solution is characterized by its simplicity and clarity, making it more readily implementable into computer programs for conducting preliminary assessments of one-dimensional consolidation in unsaturated soil.

2.3.3.5 Zhou et al. (2021)

This study sought to develop a comprehensive semi-analytical solution for evaluating the one-dimensional consolidation behavior of multi-layered unsaturated soil subjected to both impeded drainage boundaries and time-dependent loading. Additionally, two case studies were presented to elucidate the consolidation behavior of multi-layered unsaturated soil, along with discussions on the influences of impeded drainage parameters. When external loads are applied to multi-layered unsaturated soil, distinct excess pore-air pressure and excess pore-water pressure developments occur across different soil layers.

2.3.3.6 Huang et al. (2021)

In this study, we introduce a comprehensive analytical solution for predicting the axisymmetric consolidation behavior of unsaturated soil, incorporating impeded drainage boundary conditions in both radial and vertical directions simultaneously. Overall, the general analytical solution and findings of this study contribute to a better understanding of axisymmetric consolidation behavior in unsaturated soil, particularly relevant to ground improvement projects with vertical drains and the gas-oil gravity drainage mechanism in naturally fractured reservoirs.

2.4 Summary

The present chapter provides a comprehensive literature review on the prediction of consolidation behaviour in saturated and unsaturated soils. A summary of the research works that had earlier addressed the initial conditions (i.e. load-induced instantaneously generated excess pore pressures), boundary conditions (i.e. flexible drainage boundaries), loading type (e.g. ramp, cyclic), flow characteristics (linear/nonlinear), stress-induced heterogeneities, and variable saturation state are presented very briefly. The literature reviews are also carried out for the coupled consolidation. After conducting a rigorous literature review, it is well identified that there are a few unaddressed avenues that require detailed numerical investigation. In connection with the research gaps, it is required to reassess the consolidation process by incorporating the following aspects:

(a) various shapes of initial pore pressure distribution on the homogenous/ layered clays with different degrees of saturation.

(b) the spatial gradient along with the stress gradient of the permeability function.

(c) combined influences of stress-dependent permeability and compressibility, non-Darcian flow, and ramp loading

(d) combined influences of cyclic loading, semi-permeable drainage boundaries, and non-Darcian flows

(e) combined influences of semi-permeable drainage boundaries, and non-Darcian flows for unsaturated clays.