CHAPTER 1

Introduction

1.1 GENERAL OVERVIEW

External disturbances (such as external loadings and climatic changes) on fine-grained saturated/unsaturated soils develop excess pore pressures instantaneously. The generated excess pore pressures subsequently dissipate and thereby tend to establish the equilibrium state that exists before the applied disturbances. Owing to its low hydraulic conductivity, the fine-grained soil consumes a considerable time lag (maybe in years or decades) between the generation and complete dissipation of the initial excess pore pressures. The dissipation of pore pressures eventually results in effective stress changes and subsequent vertical deformation of the fine-grained strata. The transient process of pore pressure dissipation (and resulting settlement) is technically known as "primary consolidation". The phenomenon of "secondary consolidation" happens predominantly for the organic clays and is attributed to the delayed rearrangement of the particles to attain the dense configuration. Most of the literature assumes the secondary consolidation to occur after the end of the primary consolidation. The consolidation process mentioned in the present thesis focuses only on primary consolidation. Understanding the consolidation-induced settlement and its rate is crucial in various structures built on fine-grained soils. Terzaghi (1925) was the pioneer to conceptualize and devise the consolidation in fine-grained soil. The time lag between generation and dissipation of pore pressure is due to the low permeability of the fine-grained soil. The fundamental physical processes of consolidation were mathematically explained (Terzaghi and Frohlich, 1936) by utilizing the effective stress principle. Terzaghi's one-dimensional consolidation theory stands out as one of the most significant advancements in geotechnical engineering for saturated soils.

Later, Fredlund and Rahardjo (1993) extended Terzaghi's consolidation theory to predict the consolidation behaviour of unsaturated soil. Nonetheless, owing to the model complexities and inadequacies in computational flexibilities, the classical consolidation theories were developed based on several assumptions (as mentioned in the next section). The assumptions are related to the clayey layer's physical and mechanical properties, the flowing fluid's properties and its flow mechanism, the geometrical configuration of the clayey layer, the drainage boundaries, the applied loadings, and other mechanical responses. In the last few decades, a series of numerical and analytical experimentations have been performed to overcome these assumptions and predict the consolidation process more realistically. In the present thesis, an attempt has been made to revisit the consolidation analysis from a realistic perspective by removing some of the drastic idealizations.

1.2 ASSUMPTIONS IN THE CLASSICAL CONSOLIDATION THEORY

1.2.1 Material properties

- Soil is inherently homogenous and isotropic continuum medium.
- Soil solid and water are incompressible. Soil mass is weightless.
- The coefficients of compressibility and conductivity (fluid) are stress-independent.

1.2.2 Flow properties

- The flow is completely laminar, irrotational, and inviscid.
- The flow velocity and hydraulic gradient are linearly related through Darcy's law.
- The fluid flow occurs only along the direction of load application.
- The fluid properties are assumed to be unaffected by the change in temperature, viscosity, or density.

1.2.3 Drainage boundary

- The drainage boundaries are extreme- either completely drained (fully pervious) or completely undrained (fully impervious). Fully pervious boundaries are realized by considering the field variables (excess pore pressure) to be zero; whereas, fully impervious boundaries are modelled by fixing the space gradients of the field variable to be zero. It can be inferred that for fully pervious boundaries, the velocity of the fluid is infinite (indicating no pore pressure), whereas, for fully impervious boundaries, the velocity of the fluid is zero (indicating no flow).

1.2.4 Loading characteristics

- The load is applied instantaneously and only in the vertical direction.
- The applied load is continuous (strip) and time-independent.

1.2.5 Geometric configuration

- The ground surface is completely horizontal and flat (no inclination) before and after the consolidation.
- The soil is extended infinitely in the lateral direction (plane strain condition).
- The vertical pore pressure distribution between the top and bottom drainage boundaries remains the same at any location beneath the loading pad.

1.2.6 Mechanical response

- The pore pressure distribution is evaluated by the uncoupled analysis, i.e., stress equilibrium equations are not used. The average deformation of the consolidating layer is calculated separately using constitutive equations.
- The small strain theory is used. The strains are calculated from undeformed geometry (i.e., Green-Lagrange Strain is used).
- Soil settles only in the vertical direction, i.e., lateral strain is constrained.

- The applied energy is not sufficient to cause particle breakage.
- Secondary consolidation occurs after the completion of primary consolidation. The creep effect is not considered.

1.3 BRIEF OVERVIEW OF CONSOLIDATION PROCESS

1.3.1 For saturated soil

Saturated soil comprises of two-phase system- solids and water. The application of external pressure induces an *initial excess pore water pressure* (u_0) throughout the depth of the soil layer in addition to the existing static pore water pressure within the soil. This additional PWP is equal to the applied external pressure and it dissipates over time, which leads to the transient settlement. The saturation stage will remain the same throughout the consolidation process. Terzaghi's classical derivation of the *pore water pressure* (PWP) dissipation in saturated soil includes a constitutive equation and flow law. The constitutive equation relates the soil structure deformation with the stress change by using the constant compressibility parameter (m_v). The water flow follows Darcy's linear relation where the flow rate of water is related to its hydraulic head gradient by employing the coefficient of permeability (k).

The continuity of a saturated soil element requires that the volume change of a soil element be equal to the volume of water expelled from the element. After applying the continuity equation, linear velocity-gradient relation, basic soil volume-mass properties, constant load criterion, and the other assumptions mentioned above, the classical formulation of 1-D PWP dissipation takes the following form:

$$c_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{1.1}$$

where, (i) u, the excess PWP, is function of time (t) and space (z), and (ii) c_v refers to the coefficient of consolidation. The parameter c_v embodies the permeability and compressibility characteristics in a single parameter. The spatial and temporal change in u results in a change of effective stress ($\sigma' = \sigma - u$), which eventually causes vertical settlement to occur.

1.3.2 For unsaturated soil

Following Fredlund and Morgenstern (1977), unsaturated soil comprises of four-phase system: solids, water, air, and contractile skin. Unlike saturated mechanics, both pore air and the contractile skin significantly affect the mechanical properties of the unsaturated soil. The contractile skin, which is characterized by the air-water interface, brings soil particles closer through surface tension and behaves like an elastic membrane. Under the applied stress gradient, the soil particles and contractile skin come to equilibrium, whereas the air and water start to flow. As the volume change of the contractile skin is internal to the element, therefore, the total volume change of an infinitesimal element equals the sum of the volume change of the water and air phase. The volume change of each phase depends on two independent stress state variables namely, net normal stress (σ-u_a) and matric suction (u_a-u_w); σ, u_a, and u_w are the total normal stress, pore-air, and pore-water pressures, respectively. Hence, there are two compressibility parameters for each phase, resulting in a total of six compressibility parameters, of which four are independent. Generally, the compressibility parameters for the soil structure and the water phase are determined but the compressibility parameters for the air phase are derived from the continuity equation. Due to the action of the four compressibility parameters (as opposed to one for saturated soils), the prediction of consolidation for unsaturated soil is much more complicated than the saturated soil.

The application of external load generates *initial excess pore water* (u_{w0}) and *pore air* (u_{a0}) *pressures* in unsaturated soil which dissipates over time. The magnitude of u_{w0} and u_{a0} for imposing the initial constraints are determined by using the compressibility of the air-water mixture. It should be noted that not only u_{w0} but even the summation of u_{w0} and u_{a0} is notably less than the applied stress. It appears that the initial excess pore pressures depend on the degree of saturation (S), porosity (n), and volume compressibility moduli related to the net normal stress and matric suction. With the advancement in time, the induced excess pore pressures get dissipated and return to the equilibrium state that existed prior to loading. The dissipation of pore pressures leads to an increase in the matric suction and net normal stress.

Fredlund and Rahardjo's (1993) one-dimensional consolidation theory is widely accepted and comprehensively used for predicting the tempo-spatial variation of excess pore pressure dissipations in the vadose zone. By considering the linear flow of water and air, the consolidation phenomenon is simulated by the following two partial differential equations:

$$\frac{\partial u_w}{\partial t} + C_w \frac{\partial u_a}{\partial t} = c_v^w \frac{\partial^2 u_w}{\partial z^2} \tag{1.2a}$$

$$\frac{\partial u_a}{\partial t} + C_a \frac{\partial u_w}{\partial t} = c_v^a \frac{\partial^2 u_a}{\partial z^2} \tag{1.2b}$$

where, (i) C_w and C_a are the interactive constants associated with water and air phases, respectively; (ii) c_v^w and c_v^a are the coefficients of consolidation for water and air phases respectively. The governing differential equations are formed to derive the space and time-dependent field variables (u_a and u_w) by considering all the previously mentioned assumptions and some additional assumptions regarding the air phase.

1.4 MOTIVATION AND OBJECTIVE OF THE WORK

Terzaghi's one-dimensional consolidation theory was developed based on the idealizations of various aspects. This theory provides closed-form analytical solutions for assessing the compressibility of saturated clays. Since its development, this theory has been used to calculate the consolidation settlement of various geotechnical projects. Despite its widespread use, this analytical model has limited predictive capabilities due to the inherent assumptions. The extended version of the unsaturated consolidation, as demonstrated by Fredlund and Rohardjo (1993), also suffers such limitations.

To accurately represent the real-life field scenario, certain assumptions must be removed. Like, the assumption of uniform u_0 distribution is not reasonable, especially for slurry consolidation, shallow footing placed over thick consolidating layer, pre-consolidated clays, etc. The non-uniform distribution of u_0 is not merely theoretical but also supported by empirical evidence from field studies like the one carried out by Chu and Wan (2005). Depending on factors such as soil type, applied loading, drainage boundaries, layer thickness, and stress history, variously shaped (linear/ nonlinear, symmetric/asymmetric) initial excess pore pressure distribution may develop in the field. However, the existing consolidation studies have been restricted to a limited set of pore pressure distributions, focusing exclusively on homogenous soil. An approach is also required to be devised to represent the spatial variation of maximum pore pressure in a single graph for more comprehensive insights.

Other aspects explored in this thesis include the flow behaviour, loading pattern, material parameters, drainage boundaries, and saturation state. It is well established in the previous literature that due to the presence of the lower hydraulic gradient in clays, Darcy’s linear flow fails to capture the actual velocity of the pore water flow. A non-linear velocity-gradient relationship must be invoked to accurately predict the transient flow and settlement. The assumption of constant and instantaneous load is also not practically feasible. The time-dependent load (e.g. ramp loading, cyclic loading) mimics the real-life load application to some extent. The ramp loading replicates the load during the building or embankment construction whereas, the periodic loading symbolizes the traffic loading. It is noteworthy that the mechanisms of consolidation settlement under static and cyclic loading differ significantly, and hence, a separate and detailed investigation is required. Furthermore, the hydraulic conductivity and the compressibility of the consolidation layer might be inherently homogenous but depend highly on the induced stresses. With the advancement in the consolidation process, the effective stress changes with time and space; thus, resulting in variable void ratio and subsequent change in permeability and compressibility. Considerations of stress-dependent parameters are crucial for reliable anticipation of the consolidation settlement. There is also a need to revisit the conventional drainage boundaries which are extreme – either completely drained or completely undrained. However, the change of the field variables or their gradients at the boundaries are not sudden; they are gradual. The boundary conditions are even susceptible to change over time due to the migration of fines with the fluids during the process of consolidation. To model the level of drainage obstruction at the top and bottom surfaces of the consolidating layer, impeded boundary conditions are required to incorporate. However, the combined effect of permeability variation and non-Darcian flow is unexplored. Moreover, there is a dearth of comprehensive research that thoroughly investigates the coupled consolidation for impeded boundary conditions along with non-Darcian flow and cyclic loading.

In contrast to saturated consolidation, the study of unsaturated consolidation is significantly less extensive. However, considering the groundwater table location and its fluctuation, studying the consolidation of variably saturated soil has garnered significant interest in the last two decades. Most of the aspects mentioned above are required to be incorporated for the unsaturated clays as well. No literature seems to be available that addresses the consolidation of unsaturated soil with semi-permeable drainage boundaries and non-Darcian fluid flow.

Considering these research gaps, the following objectives are chosen to be addressed in the present thesis:

i. Studying the effect of non-uniform initial excess pore pressure distributions for saturated and unsaturated clays. For unsaturated clays, the nonuniform shape will be imposed on air and water phases both.
ii. Studying the effect of non-Darcian flow on the saturated and unsaturated consolidation.
iii. Analyzing the impact of stress-dependent permeability and compressibility on the overall consolidation of saturated soils.
iv. Investigating the effect of semi-permeable boundaries on the consolidation behaviour of saturated and unsaturated soils.
v. Investigating the impact of time-dependent loading (ramp and cyclic loading) on the process of consolidation. Understanding the impact of continuous loading and unloading on the consolidation mechanism while the applied load is periodic in nature.
vi. Incorporating Biot’s form of coupled consolidation equation to understand the variation of the spatial deformation while analyzing the pore pressure dissipation of saturated clays subjected to periodic loading.

Incorporation of the abovementioned aspects in the consolidation behaviour, eventually gives rise to the nonlinear partial differential equations (PDE). The non-linear PDEs are difficult to solve through analytical methods. To simplify the solution procedure, the numerical Crank-Nicolson semi-implicit finite difference scheme is employed for solving the nonlinear diffusion equations by suitable discretization.

1.5 ORGANIZATION OF THE THESIS

The present thesis is organized into nine different chapters. This chapter focuses on the motivation behind the thesis and provides a brief overview of the research conducted within it.

Chapter 2 presents a brief review of the literature associated with the impact of the five aspects (non-uniform initial excess PWP, non-Darcian flow, varying permeability and compressibility, time-dependent loading, impeded boundary condition, and variable saturation state) on the overall process of consolidation of fine-grained soil.

Chapters 3–6 primarily address the consolidation of saturated soil, while chapters 7 and 8 focus on the consolidation of unsaturated soil.

Chapter 3 shows how the consolidation of saturated soil is influenced by various symmetric and asymmetric shapes of initial excess pore water pressure distribution. The analyses are carried out for homogenous and two-layered saturated clays subjected to one-way and two-way drainage boundaries. A series of investigations are carried out by varying the geometrical and material properties of the consolidating layer.

Chapter 4 primarily focuses on the impact of stress-dependent flow and compressibility characteristics. The first section of the chapter aims to demonstrate the extent of variation in consolidation if the stress gradient of permeability is not integrated along with the spatial gradient of permeability. The second section demonstrates the combined effects of non-Darcian flow, ramp loading, and stress-induced heterogeneity on the transient dissipation and subsequent settlement.

Chapter 5 deals with the Biot’s consolidation of the homogenous soil. It thoroughly examines the effects of an impeded boundary condition for cyclic loading, in addition to examining the impact of non-Darcian flow on the rate of consolidation in detail. The settlement isochrones and the normalized settlement magnitude throughout the consolidation process are also depicted.

Chapter 6 deals with solving the non-linear equation of consolidation along with non-Darcian flow by using the Newton Rapson method.

Chapter 7 presents the influence of various shapes of symmetric and asymmetric initial excess pore water pressure on pore pressure dissipation of unsaturated soil by assuming constant load applied on the soil layer. The impact of porosity, degree of saturation, and various compressibility parameters on the generation and dissipation of excess pore air and pore water pressures are studied extensively.

Chapter 8 shows the combined impact of impeded boundary conditions and non-Darcian flow on the consolidation of the homogenous unsaturated soil. The demonstration reveals the influence of the air-water permeability ratio on the rate of consolidation. Chapter 9 concludes the findings of the thesis and discusses the scope for performing future research work.