CHAPTER 9

Conclusions and Future Recommendations

9.1 CONCLUSIONS

The present thesis demonstrates the various modifications in conventional theories of consolidation for saturated and unsaturated soil. The numerical simulations are carried out with the aid of the Crank-Nicolson finite difference scheme. Based on the findings, the following conclusions are drawn from the thesis:

- The effect of various initial PWP distributions on the consolidation of a homogenous and isotropic clayey layer, subjected to single and double drainage conditions, are presented in terms of the normalized isochrones, consolidating curves, and a newly developed 'u_{max} path approach'. The u_{max} path provides a highly efficient local and global scale representation of pore pressure dissipation for several variables in a single graph. The shape of u_0 distributions plays a significant role in the overall consolidation behaviour. For any u_0 distribution, irrespective of its linearity and symmetricity, if the maximum PWP lies at or near the mid-surface of the clays, the process of consolidation appears to decelerate. On the contrary, as the u_0 gets concentrated near the drainage surfaces, the rate of dissipation increases. Surprisingly, for a two-way drainage system, if u_{0max} lies at one of the drainage surfaces, the dissipation rate seems unaffected by the magnitude of u_0 developed at the other drainage boundary. Pore pressure redistribution was observed in both single- and double-drained layers, with some parts of the soil layer experiencing an increase in excess pore water pressure above their initial u_0 values. In single-drained layers, redistribution was prevalent when the initial excess pore water pressure distribution had minimal values at the impermeable boundary.

- The influence of u_0 distributions in two-layered clays is thoroughly examined by varying the permeability, compressibility, and thickness of the layers. The discussions are based on (i) isochrones, (ii) the locus of the maximum excess pore water pressure position, (iii) settlement curves, and (iv) the rate of dissipation ratio curves. The impact of u_0 loadings is found to be more significant for two-layered clays compared to homogeneous clays. The analyses demonstrate that the forms of the assumed u_0 loadings significantly impact the consolidation process. Unlike the usual observation of compression, some u_0 distributions (e.g., skewed) result in negative U_{avg} for the consolidating layer for a considerable period.
- The consideration of stress-induced heterogeneity affects the overall consolidation process to a great extent. It was shown that the conventional consolidation curve tremendously differs from the consolidation curve generated by considering non-zero stress and spatial gradient of the permeability function. The results indicate that the quasi-permeability leads to a faster rate of consolidation than the total permeability variation. The ratio of C_c to M (compressibility to permeability) significantly affects the consolidation, with $C_c/M > 1$ causing delayed consolidation and $C_c/M < 1$ leading to faster consolidation. For $C_c/M = 1$, the equation aligns with Terzaghi’s (stress-independent) expression. The magnitude of the applied load also influences the consolidation rate if the induced stresses impact the permeability and compressibility of the layer.
- The study reveals that assuming constant permeability overpredicts the consolidation rate compared to assuming variable permeability. The impact of construction time and flow type is significant for PTPB as opposed to PTIB. The Darcian flow overpredicts the consolidation rate resulting in a faster consolidation. The effects of stress on the flow and the compressibility parameters are

characterized by four parameters: A, B, C_c, and M. Higher A intercept values lead to greater void ratios and permeability, resulting in faster consolidation. Conversely, decreasing B increases permeability and speeds up consolidation. Lower B values cause notable deviations between the constant and variable permeability under PTPB. The parameter C_c affects soil stiffness and consolidation rates; higher C_c values decrease initial permeability and slow down the speed of consolidation. In less stiff soils (i.e. high C_c), the divergence between the constant and variable permeability is maximum under PTPB. The parameter M significantly influences consolidation time; higher M values increase vertical permeability and accelerate the consolidation rate.

- During the application of loading and unloading cycles, the soil ultimately reaches an equilibrium state where the consolidation and settlement curves begin to oscillate within specific ranges. The widths of these ranges are termed D_u and D_s for the consolidation and settlement curves, respectively. A consolidating layer with high drainability will attain this equilibrium state in a relatively short time; this time will be further reduced if the flow becomes linear. As the ratio of the loading period to the rest period increases, D_u initially decreases to a certain point, then begins to increase, and eventually becomes constant, irrespective of the loading pattern and flow type. For trapezoidal and triangular loading, D_u is initially greater for Darcian flow, but after a certain number of load cycles, D_u for non-Darcian flow surpasses that of Darcian flow. However, for rectangular loading, D_u for non-Darcian flow is always smaller. Conversely, the Darcian flow manifests higher D_s, indicating an overestimation of soil settlement. For non-Darcian flow, if the drainability of the bounding surfaces reduces below a certain level, D_s almost diminishes. The rectangular loading predicts maximum D_s than its triangular and trapezoidal counterparts.

- Rather than using the conventional approach of forced linearization, the consolidation behavior with exponential flow is analyzed by considering the nonlinear diffusion equation in its proper form. It is observed that even if the time increments are kept sufficiently small, there is still a possibility of an appreciable deviation between the conventional and present approaches for high non-linear systems. The modified approach predicts a slower rate of consolidation. The analysis reveals that if the non-Darcian part is evaluated at the current time state instead of the previous time state, although the simplicity of dealing with the linearized equations is compromised, the solutions will be closer to reality
- A comprehensive numerical investigation is carried out to examine the combined effect of impeded drainage boundaries and nonlinear fluid flow on the one-dimensional consolidation of unsaturated clays. It can be concluded from the study, that variations in non-Darcian model parameters, the permeability ratio of fluid phases, and the drainability at the top and bottom surfaces highly impact the rate of consolidation. The permeability of the air and water phases influences the settlement curves at early and later stages of consolidation, respectively. The effects of non-Darcian flow become apparent after excess pore air pressure is fully dissipated. The water phase consolidation curves feature two segments separated by a horizontal plateau, the extent of which is highly dependent on water phase permeability.

9.2 LIMITATIONS AND SCOPE FOR FUTURE WORK

In the entire thesis, the parabolic partial differential equations are solved through the numerical finite difference (FD) scheme. Therefore, the obtained results are not closed-form exact solutions, rather, these solutions are approximate in nature because of the discretization, truncation, and round-off errors involved in the FD scheme. Many avenues are either unaddressed or grossly simplified. The present computations are carried out with a deterministic set of u_0 distributions, inherently homogenous flow and compressible properties, and time-independent drainage boundaries. The randomness in the material properties and the initial conditions are the field reality and therefore, requires to be incorporated. The entire analyses are performed based on the estimations and interpretation of the pore pressure dissipation. The strain-based consolidation theory also needs to be employed for better comprehension. This thesis considers that only the pore pressure dissipation contributes to the progress of consolidation, so the total stress is constant throughout the consolidation process. This conforms with the assumption of one-dimensionality of strain. The consolidating layer is assumed to be isotropic and weightless. No viscous component is also attached in the analysis.

The present analysis considers the drainage boundaries (completely drained, completely undrained, or semi-impermeable) to remain constant during the entire consolidation process. In real-field scenarios, these boundaries can shift from permeable to impermeable over time due to clogging. Time-dependent drainage boundaries provide a more flexible framework to model these dynamic situations and provide insights into the consolidation mechanism more realistically.

The results presented in this investigation pertain exclusively to one-dimensional consolidation. However, extending this theory to three-dimensional consolidation could provide a more comprehensive analysis by considering coupled consolidation effects, including the Mandel-Cryer effect. This approach could lead to more precise predictions and improved geotechnical designs by capturing the complexities of real-world scenarios.

While modeling the unsaturated consolidation, the vadose zone was presumed to have a constant degree of saturation. However, it is well established in the literature that the saturation and subsequently the permeability above the groundwater table (GWT) varies significantly due to the change in the matric suction. For a particular soil, the impact of matric suction on the water volume and the permeability are characterized by the soil water characteristics curve (SWCC) and hydraulic conductivity curve (HCF), respectively. Moreover, in the present thesis, the possibility of the existence of GWT within the clay layer is not explored. In real field scenarios, the water table often lies between the top and bottom drainage surfaces of the consolidating layer, creating distinct regions of saturation and partial saturation zones. The inclusion of SWCC and HCF, and the flexibility of GWT fluctuations can lead to better predictions of unsaturated soil consolidation.