

## CONCLUSIONS AND FUTURE SCOPES

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### 10.1 CONCLUSIONS

In the present thesis, static and seismic stability analyses of various slopes and retained backfills are performed. The analysis of saturated soil slope problems is performed by considering the Mohr-Coulomb yield criterion, while for rock slope problems, the Hoek-Brown yield criterion is employed. Furthermore, the problems related to unsaturated soil slopes and retained backfills are addressed by duly modifying the Mohr-Coulomb yield criterion, incorporating the suction-stress-based effective stress approach. During the analysis of slope stability problems, two analytical methods, namely the variational method and the upper bound rigid block method, are suitably modified and then utilized. Additionally, a numerical method known as the strength reduction method has been employed. For addressing earth pressure on retained backfill problems, the limit equilibrium method has been applied. The work presented in the thesis leads to the following conclusions:

- On the basis of modified variational formulations for soil slopes, design charts in terms of the critical factor of safety ( $F_s$ ) are prepared by considering various soil properties, slope geometries, and seismic forces. The nonlinear decrement of  $F_s$  with the increase in seismic activities and soil weakening is properly established. Furthermore, both static and seismic cases reveal a significant reduction in the factor of safety with an increase in slope angle.
- Additionally, the variational formulations are further extended to examine the stability of generalized homogeneous rock slopes under the influence of seismic

forces. The stability charts are presented by considering six parameters, which include: (i) slope geometry ( $\beta, h$ ), (ii) material properties of the rock mass ( $GSI, \sigma_{ci}$  and  $m_i$ ), and (iii) horizontal seismic acceleration coefficient ( $k_h$ ). It is noticed that with a constant value of  $m_i$ , the critical factor of safety ( $F_s$ ) shows significant improvement as the  $GSI$  value increases. It is also noted that when  $GSI$  remains constant, the relationship between  $F_s$  and  $m_i$  does not exhibit a specific trend. For lower  $GSI$  values (10, 30, and 50), the curve between  $F_s$  and  $m_i$  demonstrates an increasing trend, while for  $GSI=100$ , the pattern is characterized by a decreasing trend. Further, it is observed that the stability of the slope improves with higher values of  $\sigma_{ci}$ .

- The stability of two-layered soil slopes is examined by using a numerical approach called the strength reduction method. A set of upper and lower bound limit analyses are conducted in Optum G2 software by introducing stronger layers of varying thickness on top of the weaker layer. To assess stability, charts are proposed for different combinations of soil properties, slope shapes, and thickness of the top layer. The improvement of stability by the placement of a stronger layer above the weaker stratum becomes more prominent for steeper slopes. It is noticed that within a particular limit of top layer thickness, the stability of the slope is significantly affected by the strength properties of the bottom layer. Furthermore, there exists a specific ratio of top layer thickness to the overall depth ( $t/D$ ) beyond which there is minimal improvement in the stability of slopes. This specific thickness is referred to as the optimum thickness ( $t_{opt}/D$ ).
- A new methodology is proposed for determining the closed-form  $F_s$  for unsaturated homogeneous soil slopes by using the modified form of VM. The

usage of VM for solving unsaturated soil slopes is the first of its kind. Climate change-induced spatial flow of water gets aptly modelled in the proposed approach. A rigorous parametric study is performed by varying the slope geometry, unsaturated soil properties, soil strength, water flow behavior, and the water table position. An effort has been undertaken to analyze the stability of slopes under the influence of transient infiltration. The key observations are: (a) irrespective of the pore-size distribution (represented by  $n$ ) the stability number decreases as the air entry value increases, (b) the stability improves with  $n$  until a certain air entry value is reached, beyond which there is no further increase in the magnitude of the stability number, and (c) with the advancement in time, the transient profiles approach the steady-state curve. Additionally, it is consistently observed that the stability for steady-state flows always remains higher than the transient curves, regardless of the shape of the slope and the strength of the soil.

- By using the upper bound rigid block method, a detailed investigation is carried out to understand the effect of seismic loadings and surcharge pressures on the stability of homogenous, unsaturated slopes. The study accounted for various factors, including the depth of the water table, unfavourable climatic conditions, and different slope geometries, which have a notable impact on the stability of slopes. Regardless of the unsaturated soil properties, the stability profiles show an increasing trend with the lowering of the water table. The stability number for  $\alpha=0.01 \text{ kPa}^{-1}$  remains always higher than the stability number computed for  $\alpha = 0.1 \text{ kPa}^{-1}$ . It is important to note that the values of stability number decrease in the following order of flow conditions: evaporation > hydrostatic > infiltration > no-suction (saturated). The three-dimensional figures are presented

to showcase the combined effect of surcharge pressures, seismic loadings, and unsaturated soil properties on the stability values.

- The earth-pressure coefficients for unsaturated retaining soil backfill are determined by incorporating the matric suction effect. The use of suction-stress-based effective stress formulations provided flexibility and wider applicability in stability analysis. Unlike conventional practices, the strict constraint on the asymmetry fitting parameter of the soil-water characteristic curve (SWCC) is relaxed, allowing for a more accurate determination of earth pressure coefficients in different soil states (rest, active, and passive). The study also explores two-parameter-dependent permeability models, concluding that while the independence of the residual-state-controlling parameter is crucial for modeling real field scenarios, the traditional one-parameter permeability model remains reliable for retaining wall analysis. The modified Coulomb's earth pressure theory is explicitly used for verifying the effect of wall inclination on the computed active earth pressure behind the inclined unsaturated backfills under seismic activities. The active earth pressure coefficients decrease continuously with the increase in water table depth, air entry value, slope angle, and friction angle. The three-dimensional charts are prepared accordingly.
- The seismic lateral earth pressure developed in retained unsaturated backfills under transient infiltration has been computed by taking into account the variation of suction stress over time and space. The suction-stress-based effective stress formulation encompasses a finite-difference solution for one-dimensional transient unsaturated flow. The tension crack depths are also thoroughly examined. The significant observations from the study are outlined as follows: (i) The suction stress results in nonlinear earth pressure profiles. The

inclusion of suction stress either generates additional tensional stresses (for the active state) or imparts extra compressive stresses (for the passive state), (ii) The seismic earth pressure coefficients (both active and passive) for unsaturated soil depend on the seismic loading, infiltration characteristics (rate and duration), saturated strength parameters, SWCC model parameters, space- and time-dependent matric suction, and vertical overburden pressure. With time, the active earth pressure coefficient increases, but the passive earth pressure coefficient decreases, (iii) Irrespective of the failure state (active or passive), the size of the Mohr failure circle reduces with the increase in seismic loading and infiltration duration. The contraction of the Mohr's circle eventually weakens the soil shear strength either by reducing the failure envelope's slope (for high seismic loading) or by narrowing the  $\tau$ -intercept (with elapsed time). Up to a certain level of seismicity, the profiles of the maximum obliquity angle and the seismic intensity are linear and parallel, (iv) As time progresses, the matric suction profiles consistently move from the hydrostatic line to the zero-suction line; however, the time-varied (normalized) suction stress profiles hover on either side of the 0-day  $\sigma_{norm}^s$  profile. The effects of infiltration rate on the suction profiles are realized over time. Unlike the trend of the  $\sigma_{norm}^s$  curves, the  $\psi_{norm}$  profile monotonically increases with time, irrespective of the soil type and infiltration rate, (v) The overall volume of the tensile zone (developed at the active state) near the ground surface gets smaller with the increasing infiltration duration and intensity. For a moderate infiltration rate, the closure of the crack openings and the reduction in the lateral spread of the tensile zone takes a very long time, (vi) The consequences of the transient phenomenon are prominently visible for the fine-grained soils. Furthermore, the ramifications of transient

flow are quite higher on active earth pressure profiles than its passive counterpart. Thus, the transient analysis of matric suction for silts and sands hardly plays any role in normalized earth pressure profiles generated from the passive state, (vii) The tensile crack zone attenuates due to the application of seismic loading. In short, the influence of seismic load turns the earth pressure profiles linear and suppresses the effect of transient flow, (viii) The tensile crack grows larger for the soil with high air entry value under static loading and experiencing shorter infiltration.

## **10.2 SCOPE FOR FUTURE WORK**

Future work may proceed in various directions. Some of the following points may be noted for future prospects in this field:

- The seismic analysis, in this thesis, is performed by employing the pseudo-static approach. The inertial effects of dynamic loading are not precisely included in the present analysis. There is future scope to perform the saturated and unsaturated stability analysis by reformulating the slope stability and earth pressure problems by using pseudo dynamic approach.
- The water flow within the vadose zone is idealized by the linear Darcian flow. However, it is well observed in the literature, that the hydraulic flow within the fine-grained soil with low hydraulic gradient is non-Darcian. Therefore, further works need to be carried out to verify the impact of non-Darcian steady-state/ transient flow on the slope stability analysis and the earth pressure calculations.

- The present analysis is based on the strength parameters alone. No stiffness parameters are considered in the analysis. The considered strength parameters are hydrostatic stress independent. The effect of stress level and strain levels are completely ignored in the present analysis. A future endeavour can be made in this regard to reformulate the analytical techniques (VM, UBRBM, LEM) by properly encountering the effect of stiffness parameters, stress-dependent strength parameters, and progressive shear failure.
- The analysis considers the soil to be isotropic, perfectly plastic, and associative. The consequence of perfect plasticity and associativity lies in the fact the hardening/ softening of the soil after the yield is ignored and an excessive dilation is considered. There is a scope to develop the formulations by duly incorporating the anisotropy, hardening/softening laws, and non-associativity laws.
- The present thesis neglects the hysteresis of the SWCC curves. There are quite a few research (Tang et al., 2017; Yuan and Du, 2018, 2020; Fathipour et al., 2023) that reveal SWCC curves are not unique. The non-uniqueness of the SWCC curves due to the drying and wetting phases, multidirectional flows, and mean effective stress- and relative density-dependencies are to be incorporated into the formulations for realistic predictions of earth pressures and slope stability.