ABSTRACT

The contributions of the thesis can broadly be viewed from the following two perspectives: (a) modification and application of variational method (VM) formulations by accounting the seismicity and heterogeneity of soil as well as rock slopes, and (b) incorporation of unsaturated soil mechanics for dealing with the slope stability and lateral earth pressure related problems.

In the first section, the variational formulations, as available for analyzing the homogenous cohesive soils (Revilla and Castillo 1977), are duly modified for accounting the frictional effect, seismicity, and heterogeneity of the soil medium. The VM is based on the fundamental principles of calculus of variation and is developed on the framework of limit equilibrium method (LEM). However, unlike the LEM, the VM formulations do not require any static (i.e., the shape of the critical slip surface) or kinematical assumption (i.e., distribution of normal stress along the slip surface). Loosely speaking, in variational method the functionals are optimized for obtaining the desired solutions. In the slope stability problems, the form of the factor of safety can be represented as the ratio of two functionals which are obtained from the available resisting and actual driving moments. The form of resisting and driving moments are functional as they are the function of the slip (unknown) and slope (known) surfaces. To determine the critical factor of safety (F_s) and corresponding critical slip surface of a slope these functionals are optimized by employing the Euler-Lagrangian (EL) equation. The usage of EL equation results in the development of an ordinary differential equation (ODE) in terms of the second-order derivative of slip (unknown) surface. The form of yield surface is obtained by adequately integrating the ODE. The unknown integrating constants, starting and ending points of the slip surface, and the magnitude of F_s is obtained by satisfying the transversality, continuity, intersection, and natural boundary conditions. The geomaterials (soils and rocks) are assumed to be perfectly plastic and as a consequence, the yield and the failure criterion are the same. The failure of soil and rock are assumed to be governed by the linear Mohr-Coulomb yield criterion and non-linear Generalized Hoek-Brown yield criterion, respectively.

In the context of the application of VM, the seismic slope stability analyses are performed on four different types of soil configurations: (a) homogeneous c-ϕ soil, (b) non-homogeneous undrained cohesive soil, (c) two layered cohesive-frictional soil, and (d) homogeneous c-ϕ soil underlain by non-homogeneous clays. For each specific case, extensive design charts are prepared to provide a comprehensive understanding of the variation of the safety functional by varying wide range of material properties, geometrical configurations, applied loadings, and the boundary conditions. The combinations of various soil properties, slope geometries, and seismic forces are crucially scrutinized. Following a few past studies, the inertial effects of the dynamic forces are idealized by pseudo-static horizontal and vertical forces. Due to the adoption of the pseudo-static analysis, the VM formulations are developed based on the static equilibrium equations. A thorough investigation is performed to establish the qualitative and quantitative relationship of the critical factor of safety (F_s) with the slope angle (β), internal friction angle (ϕ), horizontal (k_h) and vertical (k_v) seismic acceleration coefficient, increasing rate of cohesion (m), top layer thickness coefficient (α_1), cohesion coefficient (λ) of the bottom layer and other considered parameters. The form and extent of the critical slip surfaces are also reported for various considered input parameters.

Furthermore, the variational formulation is extended to accommodate homogeneous rock slopes subjected to seismic activities. The stability charts are constructed by

varying the following parameters: (i) slope geometry, (ii) rock mass properties (Geological Strength Index (*GSI*), uniaxial compressive strength of intact rock (σ_{ci}), and non-dimensional material strength parameter (m_i)), and (iii) horizontal seismic acceleration coefficient (k_h). The relationship between F_s and rock properties are established for various rock slopes subjected to different combinations of seismic forces.

Moreover, in order to assess the accuracy of modified VM, a two layered soil slope has been analyzed by using the strength reduction method (SRM), a numerical approach. The SRM comprises a series of finite element lower bound (LB) and upper bound (UB) limit analyses in conjunction with nonlinear optimization techniques implemented through Optum G2 software. It is noteworthy that the solutions obtained from VM exhibit substantially lower values when compared to the outcomes achieved through SRM.

In the first section of the thesis, the stability analyses are performed by assuming the geo-materials to be either completely dry or completely saturated. However, in a practical scenario, most of the soil slopes lie in the arid and semi-arid zones where evaporation is quite higher than precipitation and the underlying soil is in a partially saturated condition. Additionally, the fluctuations of the water table and the change in climatic conditions pose the indispensability of incorporation of the unsaturated soil properties in the slope stability problems.

The second part of the thesis focuses on solving a range of stability problems (slopes and earth pressures on backfills) considering unsaturated soils under the action of static/ seismic loadings and surcharge pressures. When addressing unsaturated soil slope and earth pressures on unsaturated backfills problems, linear Mohr-Coulomb

yield criterion is duly modified based on suction stress based effective stress approach. In the early twenty-first century, suction stress characteristics curve (SSCC) was developed by combining the Darcy's linear flow law, continuity equation, soil water characteristics curve (SWCC), Gardner's hydraulic conductivity function (Gd-HCF), and Lu and Likos's closed form relation of suction stress and matric suction. In this thesis, van-Genuchten SWCC (vG-SWCC) and Gardener's SWCC (Gd-SWCC) are adopted to model the steady-state flow and transient flow of water, respectively. The following few problems are solved by using unsaturated soil mechanics.

Firstly, a novel variational method is proposed for performing the slope stability analysis of homogeneous unsaturated soil. In-depth investigation is undertaken through a rigorous parametric study by varying the slope geometry, unsaturated soil properties, soil strength, water flow behaviour, water table position, and climatic condition (infiltration/ evaporation). Furthermore, a comprehensive study has been carried out to evaluate the impact of transient flow on slope stability. A nonlinear parabolic partial differential equation is obtained with certain constraints by consolidating the one-dimensional Richards' transient flow equation with the Gd-HCF and Gd-SWCC models. Crank-Nicolson semi-implicit finite difference method is employed for finding spatially and temporally dependent suction head and eventually, the suction stress. With the advancement in time, the transient profiles gradually converge towards the steady-state curve.

Secondly, the upper bound rigid block method (UBRBM) is used to analyze the stability of homogeneous soil slope subjected to variably saturation state, seismic loading, and surcharge pressure. The UBRBM is based on upper bound limit analysis theorem, wherein the objective function, formed by equating the external (total) work done rate and internal power (total) dissipation of the considered mechanism, is minimized to obtain the configurations of the chosen blocks at the collapse state. The log-spiral failure mechanism is adopted and the velocity field is maintained to be kinematically admissible. The plastic flow within and along the interfaces of the rigid blocks are assumed to be dictated by the associated flow rule. The incorporation of the pseudo-static loading and the surcharge pressures in computing the upper bound stability of the unsaturated slopes are the prime concern of this portion.

Thirdly, the earth pressures developed within the retained unsaturated backfills are investigated by duly modifying the classical Rankine's earth pressure theory for vertical retaining wall supporting horizontal backfills. The water flow within the vadose zone is considered to be steady-state. A detailed investigation is carried out to understand the impact of asymmetry parameter (*m*) of the vG-SWCC model and the two-parameter dependent Gd-HCF model on the computed earth pressures. In conventional analysis, vG-SWCC *m* parameter strictly depends on the pore spectrum number. An attempt has been made to reformulate and recalculate the earth pressures by duly relaxing this constraint and considering the water table fluctuations and climatic changes.

Fourthly, Coulomb's earth pressure theory is adequately modified to estimate the seismic active earth pressure developed in the unsaturated inclined backfills which are held in position by inclined retaining wall. The impact of backfill inclination, wall angle, frictional strength, unsaturated properties (air-entry value, desaturation rate) of the soil, wall-footing roughness conditions, water table positions, seismic forces, and steady-state flow characteristics (flow rate and direction) are critically scrutinized.

Finally, a series of analyses are conducted to evaluate the seismic lateral earth pressures developed in retained unsaturated backfills under transient infiltration. The effect of transient infiltration and the seismic loading on the Mohr failures circles, Mohr-Coulomb failure envelopes, pore water pressure profiles, suction stress profiles, earth pressure (active/ passive) profiles, and tension crack depths are thoroughly examined by employing Richard's equation, Gd-SWCC, and Gd-HCF model.