

INTRODUCTION

1.1. GENERAL OVERVIEW

The causes of geotechnical instability can be broadly categorized into two main groups: (i) natural causes (precipitation, earthquake, seepage, ground water flow etc.), and (ii) anthropogenic causes (deforestation, mining, excavation, reckless constructions etc.). Since the development of soil mechanics, a number of analyses are carried out to understand and properly quantify the stability of geo-structures (e.g. slopes, retaining walls etc.). Nevertheless, considering the wide variability of the geomaterials, limitation in experimental findings, drastic idealization in the existing technique, incapability of incorporating the environmental factors, the classical problems of stability analysis still remain to be challenging. Conventionally, in most of the past studies, the limit equilibrium method (LEM), a simple age-old approach, is adopted to solve the slope stability problems. However, due to statical indeterminacy arises in LEM, a few drastic assumptions are required to make up the imbalance between equations and unknowns (Duncan et. al., 2014). In the first part of the thesis, the variational method (VM) which is based on calculus of variation is sufficiently modified to accommodate the frictional effect, heterogeneity, and seismicity and applied for evaluating the stability of various slopes. Although the development of VM takes place on the framework of LEM, however, in contrast to LEM, the VM approach yields the same number of equations as the number of unknowns. Therefore, no statical (shape of the slip surface) or kinematical assumptions (distribution of normal stresses along the slip surface) are required to incorporate for obtaining the stability solution.

However, the other shortcomings associated with LEM, such as, ignoring stress-strain relationship, incapability of tackling complicated geometries, arbitrary boundary conditions, complex loading conditions, and random soil properties, are still retained with the VM. The VM primarily works by optimizing the functionals. The main components of the stability analysis are the two functionals: driving and resisting moments. These functionals are the functions of the slip surfaces. Euler-Lagrangian equation is explicitly used to optimize these functionals and to eventually provide the critical slip surface and the corresponding critical factor of safety. The VM formulations developed for the soil slopes are adequately modified to address the stability of the rock slopes. The soils and the rocks are modelled by employing the linear Mohr-Coulomb and non-linear Hoek-Brown yield criterion, respectively. For all the chosen problems, the geomaterials are considered to be isotropic, and perfectly plastic. The stability analyses of the slopes are carried out under the action of seismic loadings which are idealized with the pseudo-static forces, for the sake of simplicity.

In the second part of the thesis, the unsaturated soil mechanics are inculcated to study the stability aspects of soil slopes and backfilled soils which are under partially saturated conditions. Unlike the saturated soil mechanics, the mechanical study of unsaturated soils depends on two stress state variables, namely, net normal stress and matric suction. However, in the early twenty-first century, a number of research findings advocated the use of suction stress as the fundamental stress state variable over the matric suction. Considering that, the suction stress-based planar Modified Mohr-Coulomb yield criterion is invariably used to model the yield behaviour of the soil in the vadose zone. The used techniques are developed on the premises of the closed-form suction-stress expression which are formed by combining the van-Genuchten's soil water characteristic curve (vG-SWCC), Gardner's hydraulic conductivity function (Gd-

HCF), Darcy's linear flow law, and continuity equations. In this context, it is mentionworthy that the SWCC is the fundamental and essential tool to illustrate the engineering behaviour of the unsaturated soils. Five problems are examined under the purview of unsaturated soil mechanics --- two problems concerning the slope stability and three problems on determining the seismic earth pressures behind the retaining walls. The seismic stabilities of unsaturated slopes are determined with the aid of variational and the upper-bound rigid block methods after carrying out sufficient modifications into the formulations. The seismic earth pressures developed in the horizontal/inclined backfills that are supported by the vertical/inclined retaining walls are evaluated by duly modifying the classical Rankine's and Coulomb's earth pressure theories. The analyses are performed by considering the steady state as well as transient flow of water within the vadose zone. During the transient flow analysis, the temporal variation of suction stress above the groundwater table is computed by employing Gardner's soil water characteristic curve (Gd-SWCC).and Richard's one-dimensional transient flow equation.

The objective of the present thesis is broadly categorized into two parts. Firstly, modification of VM for stability of slopes consisting of two geo-materials such as soil and rock under saturated condition. Secondly, incorporation of suction stress in the stability of soil slopes and earth pressure developed on soil backfills.

1.2. MOTIVATION FOR THE PRESENT RESEARCH

The motivation of the present thesis stems from the urge of understanding and assessing the age-old stability problems in geomechanics from a more comprehensive standpoint. Despite the development of numerical techniques and sophistication in computational processes, the long-standing analytical methods are still used in practice

owing to their simplicity and wide acceptance. Almost all analytical works for the slope stability and retaining wall problems are conducted by different limit equilibrium methods (LEM). One of the major problems in LEM is the prior assumptions of the failure surface shape. Apart from that, few other assumptions, regarding the stress distribution along the slip surfaces and along the interfaces of the considered slices, are considered which undoubtedly compromises the accuracy of the computed solutions. These assumptions are indispensable owing to the statical indeterminacy generated in the LEM formulations. The variational method is a simple analytical technique that originates from the basic principle of calculus of variation but devoid of any such preconceived suppositions regarding the shape of the slip surface and the stress distribution along it. As per the literature survey, not much work has been done to address the stability problems through the use of variational method. The first part of the thesis aims in fulfilling some of the research gap in that context. The following few slope stability problems are solved utilizing the modified variational method:

- (i) Seismic analysis for homogenous cohesive-frictional soil
- (ii) Seismic analysis for linearly increasing cohesive soil
- (iii) Seismic analysis for different stratified soil slopes
- (iv) Seismic analysis of rock slopes

In order to validate the VM, a numerical method, namely SRM which encompasses finite element lower bound (LB) and upper bound (UB) limit analyses associated with nonlinear optimization techniques used in Optum G2 software, is employed to solve the two layered cohesive-frictional soil slopes. The primary objective of this study is to provide a quantitative estimation of the improvement in slope stability caused by placing a stronger soil layer over a weaker one.

The second part of the thesis is motivated from the limited studies of the stability of geo-structures by considering the variable saturation state of the soil above the groundwater table. In reality, most of the soil slopes and the retained backfills remains in a partially saturated state in the arid and semi-arid zones. Moreover, the fluctuation of the water table and climatic conditions play a significant role on the soil properties and gravely affect the overall stability of slopes. The usage of unsaturated soil mechanics helps in understanding the rainfall-induced instability, the drying induced cracking and their detrimental effects on the slope stability and the earth-pressure calculations. The existence of research gaps concerning the stability analysis of soil slopes and retained backfills under unsaturated conditions prompts the following studies on the basis of closed-form suction-stress expression and Modified Mohr-Coulomb yield criterion:

- (i) Formulating the variational method for addressing the seismic slope stability by duly considering spatially-varying suction stresses
- (ii) Constructing the power dissipation terms and duly modifying the upper bound rigid block method to check the effect of seismicity and surcharge pressures on the stability of unsaturated soil slopes
- (iii) Revisiting the lateral earth pressure with the modified suction-stress based Rankine's classical earth pressure theory by expanding the flexibility of one of the parameters of vG-SWCC model and incorporating the two-parameter dependent Gd-HCF model
- (iv) Examining the seismic lateral earth pressure developed within the inclined backfill and supported by the inclined retaining wall by duly modifying the Coulomb's earth pressure theory

-
- (v) Investigating the effect of transient infiltration on the computed earth pressures developed behind the vertical retaining wall

The findings from the chosen stability problems are envisioned to be useful to for the academic community as well as the practicing engineers.

1.3. ORGANIZATION OF THE THESIS

The present thesis is organized in ten different chapters. The present chapter is about the motivation and a brief description of the present research work performed in the thesis.

Chapter 2 presents a brief review of the literature associated with the development of three approaches (VM, UBRBM and SRM).

Chapters 3–9 are mainly divided into two categories of stability problems. Chapters 3–7 deal with solving slope stability problems, whereas chapter 8 and chapter 9 pertain to computation of earth pressures on retaining walls.

Chapter 3 presents the formulation and computation of stability for different soil slopes under saturated condition subjected to static and pseudo-static conditions by employing variational method. The stability assessment of several slopes of (i) homogeneous cohesive-frictional soil, (ii) two layered cohesive-frictional soil, (iii) non-homogenous cohesive soil, and (iv) cohesive-frictional soil placed on non-homogenous cohesive soil has been performed.

Chapter 4 focuses on formulating and determining the stability of homogeneous rock slope under static and pseudo-static forces using the variational method. The rock mass is modeled employing the Hoek-Brown (HB) criterion.

Chapter 5 deals with the analysis of two layered cohesive-frictional soil slopes by employing strength reduction method (SRM). The SRM applied in this study comprises a series of finite element lower bound (LB) and upper bound (UB) limit analysis in conjunction with nonlinear optimization.

Chapter 6 illustrates the formulation of the stability of homogeneous unsaturated soil slopes subjected to both steady and transient flow by using variational method. Furthermore, this chapter provides stability charts for unsaturated slopes in terms of stability number.

Chapter 7 discusses the impact on stability of homogeneous unsaturated soil slopes subjected to surcharge and pseudo-static loadings under steady flow condition with the help of upper bound rigid block method. Stability charts in terms of stability number are also proposed to demonstrate the influence of surcharge load and seismic load on unsaturated homogeneous slopes subjected to steady-state flow conditions.

Chapter 8 depicts the computation of lateral earth pressures on retaining walls backfilled with unsaturated soil subjected to static and pseudo-static forces under steady-state flow condition. This chapter divided into two segments. Firstly, relaxation on the constraints of vG-SWCC parameters and reformulate suction stress expression is carried out and applied the modified suction stress expression in the lateral earth pressures calculation. Lateral earth pressures are evaluated by modifying Rakine's classical earth pressure theory. Secondly, evaluation of active earth pressure developed in inclined unsaturated soil backfills retained by inclined wall. Lateral earth pressure profiles are also provided for different soil's hydromechanical properties, water table fluctuations, and climatic conditions.

Chapter 9 deals with the effect of transient flow and pseudo-static forces on the lateral earth pressures developed in retained unsaturated backfills. The conventional Rankine's earth theory for saturated soils is duly modified to incorporate seismic loads and the soil's partially saturated condition during the process of transient infiltration.

Chapter 10 finally summaries all conclusions drawn from the thesis and also discusses about the scope for performing future research work.