CHAPTER 1

INTRODUCTION

1.1 General

Landslide is one of the most severe natural hazards in the Himalayan Mountain ecosystem that significantly affects surface morphology. The landslide consequences may be highly disastrous in populated areas (Vasistha et al. 2011). Besides disturbing the natural fabric of the ecosystem of the area, large numbers of fatalities, severe injuries to the residents and massive economic losses have been reported from different parts of the Himalayan region owing to landslides (Bhandari 2006; Haigh et al. 1995; Jaiswal et al. 2010; Kjekstad and Highland 2009; Petley 2012). Frequent and massive landslides may drain the economy of any region as a large amount of capital is invested, especially in slope treatment and rehabilitation of the affected people (Schuster and Fleming 1986). The occurrence of landslides gets accelerated either due to natural factors (lithology, topography, morphology, hydrological regime) or anthropogenic factors (deforestation, road construction, civil & mining activities, hydroelectric project, urbanisation).

The mountain slopes can be classified into two distinct categories based on stratigraphy, namely rock slopes or soil slopes. Generally, the steep slopes ($>60^0$) are devoid of substantial soil cover and have a highly fractured rock mass cover over the bedrock. While the gentle ($<30^0$) to moderate slopes (30^0-60^0) possess a soil cover over the top of the fractured rock mass layer and are formed from the weathering of the bedrock. The depth of the soil layer varies from place to place depending on the slope inclination and the extent & rate of weathering. If the soil formed from the weathering of the bedrock stays at the location of formation, it is known as residual soil (Blight 1977). Slope failure in residual soil slope is a complex phenomenon involving various factors like slope topography, depth of soil cover, the grain size distribution of the soil, inherent heterogeneity in the geo-mechanical properties of the soil and presence of water. When the slope is covered with residual soil layer, the properties of the residual soil will influence the overall stability of the slope while the effect of rock mass gets limited (Gerrard 1994; Regmi et al. 2013). Thus, any planned anthropogenic activities in the residual soil slopes need proper and detailed scientific investigation. It is also required that such strategic slope stability assessment be performed within different vulnerable locations of the mountain ranges for a fruitful and sustainable step toward landslide hazard assessment.

Identifying vulnerable slope profiles and avoiding/taking necessary precautions is the key to the success of developmental activities in hilly areas. The behaviour of residual soil slopes depends on several factors like soil geotechnical parameters, soil depth, grain size distribution, water content, slope topography and soil rock interface strength. Therefore, for a reliable slope stability assessment, care must be taken for identifying and selecting the important parameters affecting the stability. Incorporating the inherent variability of the geomaterial properties of the selected parameters using probabilistic analysis. Further, landslide hazard charts/maps for a given regional or lithological scale must be formulated based on detailed geotechnical investigation and numerical analysis. Advance machine learning tools like Artificial Neural Network can also be used for developing stability predicting models.

The landslide hazard assessment should also include the post-disaster landslide generated debris flow analysis to ensure sustainable development of the hilly regions. Slope failure results in dislodge of a specific quantity of earth material, also known as debris, from its original position on the slope, which moves downslope owing to gravity. Debris flows are dangerous landslide-related hazards due to their long-runout, large impact force, and fast flow velocity, in association with low predictability (Choi et al. 2020; Vagnon 2020; Zhou et al. 2019a). Post failure analysis, which is often left out during landslide hazard analysis, is also essential as pre-failure stability assessment. Many debris-flow incidents are noted while carrying out various anthropogenic activities in the hills, which have an adverse impact on the downslope vegetations, human settlements and utility networks. A comprehensive understanding of the morphology and deposition mechanisms of debris flows is crucial to delineate the extent of debris flow hazards to take preventive measures and limit the damages.

1.2 Scope of the Study

Several studies have been performed in assessing the stability of rock slope, which is mainly governed by the mechanical properties and orientations of inherent discontinuities. However, the effect of discontinuities gets limited in case soil cover is present, i.e., residual soil slopes. The importance of the residual soil layer in governing the overall stability of the soil slopes has been identified by several authors (Huat et al. 2006; Hungr et al. 2014; Rahardjo et al. 2004; Regmi et al. 2013). The behaviour of residual soil slopes depends mainly on the interaction between slope topography, depth of soil cover, varying water content and percentage of fine particles. Understanding the significance and interactions of all the parameters are essential for identifying the landslide hazard potential. Further work is needed to integrate these factors while modelling the residual soil slope to increase prediction accuracy.

The presence of uncertainty in the geo-mechanical properties of the residual soil slopes makes the landslide hazard assessment more challenging. The uncertainty arises during field and laboratory testing due to the inherent heterogeneity of the geomaterial. The use of probabilistic analysis can help deal with uncertainties; however, its implementations have been restricted owing to the limited availability of data and prolonged computational time required during simulation. A large number of data is required for generating a reliable statistical distribution function of a particular parameter. However, if sufficient data representing the study area can be generated from field and laboratory tests followed by statistical analysis of the obtained data, a probabilistic slope stability assessment can be performed with high accuracy.

Landslide Hazard Zonation (LHZ) maps are generally formulated to identify landslide vulnerable areas. However, the currently available maps have incorporated limited geotechnical and topographical slope parameters. Instead, most of them are based on Geographical Information System (GIS) and Remote Sensing data merged with the current landslide inventory (Bhambri et al. 2017; Gupta et al. 1999; Mahanta et al. 2016; Mathew et al. 2007). Although LHZ maps of a larger scale based on GIS and remote sensing data give an acceptable level of information, some deviations are observed in the results. An intensive geotechnical investigation-based maps/chats that include various geotechnical and topographical parameters of the slope and the important landslide triggering factors like water content and percentage of fines in the residual soil need to be prepared. This will not only help in assessing the current state of the slope under investigation but will also help in studying the behaviour of the slope over a period of time as water content, weathering pattern and topography gets altered due to various natural and anthropogenic activities.

The data generated from the numerical analysis can be further used for developing advanced Machine Learning (ML) models for stability analysis. ML techniques like Artificial Neural Network (ANN) have been widely used to solve complex nonlinear multivariate geotechnical problems, including slope stability analysis (Das et al. 2011; Erzin and Cetin 2013; Khandelwal et al. 2015b; Kim et al. 2018; Paudel et al. 2016; Verma et al. 2016). ANN techniques are developed to learn the correlation between the factor of safety and its influencing parameters from recorded data. Previous works on ML techniques concluded that computational intelligence tools are encouraging and should be further implemented in addressing complex geotechnical problems, including stability analysis of the residual soil slope, which is absent. The studies performed by various authors are significant; however, various limitations still need to be conveyed appropriately. The primary limitations include the use of only a limited number of physical and mechanical parameters which govern the overall stability of slopes that have been used during modelling. Also, the inherent variability in the geo-mechanical properties of the geomaterial has not been taken into account in the form of input data for developing the ANN models. The previously developed ANN models have not been judiciously used to identify the importance ranking of the input variables. Thus, there is a need to develop an ANN model that will model the residual slope behaviour with a high level of accuracy.

Slope stability analysis mainly concentrates on pre-failure studies. However, slope failure results in dislodge of a specific quantity of earth material from its original position, known as debris. Debris flows are dangerous landslide-related hazards due to their long-runout, large impact force, and fast flow velocity, in association with low predictability (Choi et al. 2020; Vagnon 2020; Zhou et al. 2019a). The movement of landslide generated debris is a complex phenomenon, with many parameters that are sometimes hard to assess. Demarcating the extent of endangered areas is fundamental to landslide risk assessment. These require accurate prediction of a landslide's runout behaviour, such as how far and how fast landslides travel once mobilised. Generally, runout behaviour is a set of quantitative and qualitative spatially distributed parameters that define the destructive potential of a landslide. These parameters for landslide risk assessment mainly includes energy, velocity, runout distance, depth of the moving mass, damage corridor width, and depth of deposits which needs to be assessed (Hungr et al. 1999; Wong et al. 1997). A comprehensive study of the effect of slope topography, particle size composition and presence of water on the runout behaviour of the debris will help in developing the mitigating measure against the danger of debris flow.

1.3 Objectives of the Study

The residual soil plays a vital role in governing the stability of mountain slopes. The effect of various factors on the stability of residual soil slope needs thorough examination. The following objectives have been considered for the present study:

i. To understand the combined effect of topographical, geotechnical and hydrological parameters on the overall stability of the residual soil slope by using probabilistic analysis.
ii. To propose Landslide Hazard Charts for the Lesser Himalayan residual soil slopes formed from weathering of carbonate lithologies in the Indian states of Himachal Pradesh and Uttarakhand.
iii. To develop a slope instability prediction model for residual soil slope using Artificial Neural Networks and obtain the relative importance of the stability governing parameters.
iv. To study the effect of variation in slope topography and grain size distribution of residual soil on rheological properties of landslide generated debris under both dry and wet conditions.

1.4 Organization of Thesis Chapters

This thesis is divided into the following eight chapters:

Chapter 1 includes a basic introduction about landslides in the Himalayas, the challenges of residual soil slope failure, variability in the geo-mechanical properties of the residual soil slope, landslide hazard identification, post-failure debris flows analysis, scope and objectives of the study.

Chapter 2 reviews related literature concerning landslides in the Himalayas, formation and importance of residual soil, heterogeneity of the geomaterial and use of probabilistic analysis, various landslide hazard assessment methods, the utility of advanced machine learning techniques, post landslide debris flow analysis, and its discussion.

Chapter 3 includes the description of the study area and its discussion.

Chapter 4 includes information on site selection for data and sample collection, in-situ and laboratory tests conducted for various topographical and mechanical parameters of the residual soil slope, and its discussion.

Chapter 5 includes statistical analysis of the data generated from in-situ and laboratory tests, development of a numerical model using probabilistic analysis, formulation of landslide hazard chart using different slope physical and geo-mechanical variables, and its discussion.

Chapter 6 includes the utilisation of ML techniques like ANN for developing a highly accurate landslide prediction model for residual soil slope and to obtain the ranking for the most important parameters affecting the stability of the slope and its discussion.

Chapter 7 focuses on post-failure debris flow analysis using the distinct element method. The effect of slope topography (inclination, height and profile/curvature) and grain size distribution on the debris flow behaviour are analysed, and various flow parameters are obtained under both dry and wet conditions, the utilify of retaining wall/debris flow barrier in constraining the debris flow and their discussion.

Chapter 8 provides the conclusions made out of this research and suggestions for future scope of works.