ABSTRACT

Landslide is one of the most severe natural hazards in the Himalayan Mountain ecosystem. 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. The mountain slopes can be classified into two distinct categories based on stratigraphy, namely rock slopes and soil slopes. The rock slopes have highly fractured rock mass at the surface and are devoid of any soil cover. The failure in rock slopes is governed mainly by the discontinuities present within the rock mass. The soil slopes, on the other hand, are formed from the weathering of bedrock and are also referred to as residual soil slope. 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. It was observed that when the slope is covered with a residual soil layer, the properties of the residual soil influence the overall stability of the slope while the effect of rock mass gets limited.

In order to help the stakeholders, several Landslide Hazard Zonation (LHZ) maps were developed at various scales. However, these maps are primarily developed using limited input variables and remote sensing & GIS data. A detailed geotechnical based landslide hazard identification that had incorporated the variability of the geotechnical properties of geomaterial is found to be missing. When it comes to stability analysis of residual soil slopes, there are no specific LHZ maps available. Thus, an effort has been made to formulate Landslide Hazard Identification Chart for the residual soil slopes of the Lesser Himalayan Region formed from the weathering of carbonate lithologies. Another factor mainly ignored during landslide hazard assessment is incorporating post-failure debris flow analysis into the study. Efforts can be made to minimise the landslide occurrence, but they cannot be stopped. Landslides are inevitable; thus, a post-failure

debris flow study has also been performed to understand the flow characteristics of the debris in order to take necessary preventive measures to limit its impact.

Two sets of Landslide Hazard Chart have been proposed. The first one is a Quick Landslide Hazard Identification chart which requires three easily identifiable physical parameters of slope (slope height, slope angle and soil depth) for obtaining the probable factor of safety (FOS) of the slope. The proposed Quick Landslide Hazard Chart will be beneficial for identifying the landslide hazard for slopes under normal water content (12-20%) and percentage fine levels (14-22%). The water content and percentage fine parameters are not constant and change due to various natural and anthropogenic activities over a period of time. Thus, for studying the long-term stability of the slopes, another set of Detail Landslide Hazard Identification charts have been proposed. This set of charts has been formulated by using five parameters (slope height, slope angle, water content, percentage fine and residual soil depth) for obtaining the probable FOS of the slope.

To formulate the hazard charts, stability analysis of residual soil slope has been carried out using probabilistic numerical simulation. The residual soil slopes formed from weathering of carbonate lithologies (limestone, dolomite and dolomitic limestone) of the Lesser Himalayan region have been identified for the study. Ten sites have been selected for detailed field investigation and sample collection for laboratory tests. The residual soil of the study area is primarily loose and sandy with an average of 82.6% of coarse aggregate (gravel and sand) and the rest 17.4% of fine aggregates (silt and clay), which are mostly poorly sorted or well graded. The clay fraction varies up to 4%. The natural water content of the soil varies from 6.7% to 28.7%, with an average of 14.5%. Laboratory testing for the collected soil sample was performed under natural (disturbed) and remoulded condition (water content and fine content was varied from 0 to 30%). Several geotechnical parameters were obtained, including cohesion, friction angle, young's modulus, specific gravity, saturation level, water content and soil rock interface strength parameters (cohesion and friction angle) for the soil samples. Triaxial, Brazilian tensile, specific gravity, slake durability and Poisson's ratio tests were performed for the rock samples. Using the data from the in-situ and laboratory tests, statistical analysis was performed to obtain the statistical distribution and distribution parameters of the geo-mechanical variables of the residual soil slope. Probabilistic numerical analysis has been performed by taking several geotechnical and topographical slope parameters.

Based on the probabilistic numerical analysis, landslide hazard chats have been formulated. The proposed hazard charts have been validated with several case studies. These charts can assist investigators and policymakers during the preliminary investigation of the study area. It can help on focusing more on the vulnerable slopes. The numerical simulation data was also used to analyse the behaviour and effect of several parameters on the overall stability of the slope. It was observed that with an increase in water content and percentage fines, the cohesion increases. However, the increase is not uniform. The maximum increase in cohesion with an increase in percentage fines was observed in the case of 10% water content while the least for 0% water content. With an increase in slope angle and water content, the depth of the soil layer that will remain stable over the bedrock reduces. With an increase in the depth of the soil layer up to a certain level, the FOS reduces drastically. After that, an increase in soil depth does not significantly impact FOS.

Two Artificial Neural Network (ANN) models were also formulated (ANN1 and ANN2), using the numerical simulation data. The ANN1 was developed using the numerically simulated data generated from the testing of soil samples under natural (disturbed) conditions. This FOS prediction model corresponds to the Quick Landslide Hazard identification chart. The ANN2 was developed using the numerically simulated data generated from soil sample tested under remoulded conditions. This FOS prediction model corresponds to the Detail Landslide Hazard identification chart. The training was performed to obtain the best network architecture having a minimum root mean square error. After selecting the best network architecture (MLP 8-12-1 for ANN1 and MLP 9-11-1 for ANN2), various performance indices like the coefficient of determination, residual error, the variance accounted for, and learning rate has been utilised for assessing the efficacy of the developed ANN prediction model. Garson's equation was used to obtain the relative importance of the input parameters used during network development. The reducing order of importance of the input variable based on ANN analysis is slope angle (36.76%), water content (27.57%), soil depth (12.26%), slope height (9.09%), % fines in soil (6.36%), friction angle of soil (2.35%), young modulus of soil (2.09%), soil unit weight (1.8%) and cohesion of soil (1.73%). The results of the relative importance of the parameters were compared with the correlation analysis to validate the superior performance of the developed ANN model. Both the developed ANN model and the Landslide Hazard Charts can be used for stability analysis of the Lesser Himalayan residual soil slope (formed from carbonate lithologies).

After successfully performing pre-failure analysis of the residual soil slope, an effort has been made to simulate the post-failure landslide debris flow using the distinct element method (DEM). The geotechnical properties of the slope cannot be directly fed into DEM. Instead, it requires the particle-to-particle contact properties obtained from the hit and trial method. A physical scale down model of a residual soil slope was set up in the laboratory, and a corresponding numerical model was built in Particle Flow Code (PFC) software. The numerical model was calibrated by simulating the failure observed during the physical model testing. Using the calibrated model, a case study of the Varunavat landslide has been taken to validate the developed numerical model. After validation, several models were generated to evaluate the effect of slope height, slope angle, slope profile, and grain size distribution of the dislodged geomaterial in the rheological properties of debris flow. Both qualitative and quantitative analysis of the landslide debris flow was performed. Finally, the utility of retaining wall/debris flow barrier and their effect on debris flow are studied with different wall positions along the slope surface.

The present study has analysed the effect of various factors on both pre- and post-slope failure events in residual soil slope to achieve sustainable disaster risk reduction goals. Landslide Hazard Chats and ANN models have been proposed to identify landslide hazards using simple in-situ and laboratory tests. Debris flow studies were made to demonstrate the importance of post-failure analysis.