CHAPTER 8

CONCLUSIONS AND FUTURE SCOPE OF WORK

8.1 Conclusions

Residual soil is formed from the weathering of bedrock. The geotechnical, as well as the hydrological parameters of the residual soil slopes, gets affected due to extreme climatic condition coupled with increased anthropogenic activities. This has led to an increase in the frequency of landslides in the residual soil slopes. The bedrock has a limited impact on the stability if slopes have residual soil cover. The behaviour of the residual soil will mainly govern the overall stability of the slope. A detailed investigation has been carried out in residual soil slopes derived from weathering of carbonate lithologies of the Lesser Himalayan Region. It includes pre-failure stability and post-failure debris flow analysis. The following important conclusions have been drawn from the pre-failure stability analysis from the present study:

1. The geotechnical parameters of the residual soil slopes are not uniform. Among all the geotechnical parameters, cohesion, friction angle and young's modulus of the soil and rock mass are highly variable.
2. Most of the geotechnical variables (soil cohesion, soil friction angle, soil young's modulus, friction angle of weathered rock mass, unit weight of weathered rock mass, young's modulus of weathered rock mass, cohesion of bedrock, friction angle of bedrock, young's modulus of bedrock and tensile strength of bedrock) follow a lognormal distribution. Some of the variables (soil rock interface cohesion, soil rock interface friction angle, cohesion of weathered rock mass, tensile strength of weathered rock mass, Poisson's ratio of weathered rock mass and Poisson's ratio of bedrock) follow the normal distribution. While a very few variables (unit weight of bedrock and unit weight of soil) follow a triangular distribution.

3. The failures in residual soil slopes are primarily shallow and are limited to the soil layer only. There is a negligible impact of a thin layer (<0.5m) of residual soil on stability while keeping other slope parameters constant. However, a drastic reduction in the factor of safety was observed when the depth of the residual soil layer increased beyond 0.5m. The reduction of the factor of safety continues till 4m depth of soil layer. Further increase in depth of soil layer does not significantly affect the factor of safety of the slope.
4. The variation in factor of safety between 50m and 500m high slope is more for gentle slope having thin soil cover as compared to thick soil cover. While the variation in the factor of safety between 50m and 500m high slope is less for steeper slope having thin soil cover than thick soil cover.
5. Slope topography (slope angle, slope height and depth of residual soil layer) significant affect the stability of residual soil slope. A Quick Landslide Hazard identification chart has been formulated based on these three most important topographical parameters. The proposed chart has been validated with several case studies and can be used to quickly assess the stability state of the slope using simple in-situ observations.
6. Due to the natural and anthropogenic activities, the water and percentage fine content of the residual soil get highly affected over a period of time. So do the topography of the slope. This led to a change in the geotechnical properties and topography of the slope. The relationship between water content, percentage fine and slope topography with the factor of safety is very complex. The failure of residual soil slope does not depend on one or two parameters; instead, failure occurs at a critical combination of all these parameters.
7. A Detail Landslide Hazard chart has also been proposed using the five most important parameters (slope height, slope angle, water content, percentage fine and residual soil

depth). The proposed chart has been validated with several case studies that can be used to assess the stability state of the slope based on simple in-situ observations and a few laboratory tests. This chart can be used to study the long-term behaviour of the slope.

8. The cohesion of residual soil increases with an increase in water and percentage fine content. 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. In contrast, the friction angle of residual soil decreases with an increase in water and percentage fine content.
9. Under dry conditions (0% water content in residual soil), the factor of safety increases up to 10-15% fine content and then starts decreasing. Under the unsaturated condition, the factor of safety increases continuously up to 20-25% fine content and then starts decreasing. Under fully saturated conditions (30% water content in residual soil), the factor of safety reduces continuously with an increase in percentage fine content.
10. The factor of safety for gentle slope ($<30^0$) reduce from highly stable (FOS>1.5) to just stable (FOS~1.1) with increases in percentage fine and water content from 0 to 30% for 15m soil depth. While for the moderate (45^0) and steep (60^0) slopes, the factor of safety becomes less than 1 for more than 1m soil depth at 30% water and percentage fine content.
11. Water plays a vital role in governing the stability of residual soil slopes. Out of the 6400 slope models solved numerically, with the increase in water content from 0 to 30%, there have been an increase of 6.37% of fail slope models and 8.94% of vulnerable slope models, whereas a decrease of 15.31% of safe slope models.
12. Two Artificial Neural Network models, ANN1 (MLP 8-12-1) and ANN2 (MLP 9-11-1) was also developed corresponding to the quick identification and detail identification of

landslide hazard charts, respectively. The performance indices indicate a highly reliable prediction ability of the ANN1 (R^2 92.1%, RMSE 0.0013, VAF 95.5% and Learning Rate 0.91) and ANN2 model (R^2 98.8%, RMSE 0.0010, VAF 98.3% and Learning Rate 0.93).

13. Both the proposed landslide hazard charts and the corresponding ANN prediction models can be used to assist investigators and policymakers in identifying vulnerable slopes during the preliminary investigation in the study area.
14. 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%).

Landslide generated debris flows are fast-moving geo-material that are particularly dangerous to life and property because they move quickly, destroy objects in their paths, and often strike without warning. The debris flow analysis has also been performed in order to help understand the flow and settlement behaviour of the debris. The following important conclusions have been drawn from the post-failure stability analysis from the present study:

1. The **sorting phenomenon** was observed during the accumulation process of the flowing landslide debris. Finer particles are widely distributed near the toe of the slope and bottom of the deposit. In comparison, the coarser particles are widely distributed in the front and surface of the deposit. The presence of water also affects the final settlement of debris. The maximum distance reached by wet debris is 1.5 to 2 times, corresponding to dry debris. However, the spread is more in the case of dry debris.
2. The **kinetic energy** of the flowing debris increases with the increase in slope height and slope angle. There are almost 4 times an increase in kinetic energy per unit volume with an

increase in slope height from 20m to 100m. Increasing the slope inclination from gentle to steep slope resulted in an increase of 9 times in average kinetic energy for dry flow and 2.5 times for wet flow. However, overall, the kinetic energy of the wet debris is always more than the dry debris for a particular slope angle. Failure resulting from a high and steep slope will result in considerable damage near the toe.

3. The **maximum distance** reached by the debris flow increases with an increase in slope height. The maximum distance reached by the debris was observed in the case of moderate slope (40^0-50^0) angle and specifically for 45^0 slope. Whereas the debris flowing under gentle and steep slopes are accumulated near the toe of the slope and have a localised spread.
4. The **average velocity** of the flowing debris increased by 2.5 (under wet flow) and 4.5 (under dry flow) times with increasing in slope height from 20m to 100m. However, the average velocity of the wet debris is always more than the dry debris for a particular slope height. The average peak velocity attained by larger size particles (500-1000mm) under dry conditions is almost 3 times that of the smaller ones (1-50mm). Whereas, in the case of wet debris flow, the average velocity of all the particle sizes (1mm to 1000mm) shows an almost similar range. Thus, in the case of dry flow, only large boulders will move faster and cause much of the destruction; however, under wet flow particles of all sizes will have the potential to cause destruction.
5. The debris flowing under a concave and flat **slope profile** can destroy a wider area than that of debris flowing under a convex slope profile where the destruction is limited to the toe area of the slope. The maximum kinetic energy and velocity of the flowing debris are almost the same for the concave and flat slope profiles. In contrast, flow in the convex

slope profile, the maximum kinetic energy attained is about 60-80% and maximum velocity attained is about 75% with respect to flow under flat slope profile.

6. The **randomness** in the flow and settlement behaviour increases with the increase in the fraction of larger boulders in the debris. The debris composed of only large boulders has 7 to 30 times the standard deviation in spread than debris composed of only fines. The average kinetic energy attained by debris composed of only boulders is nearly 41 (under dry flow) and 43 (under wet flow) times higher than the case of only fine debris. While the peak velocity is almost 7 (under dry flow) and 7.5 (under wet flow) times higher. The high kinetic energy, velocity and spread of the debris (consisting of only boulders) put at risk the downslope settlements, vegetations and infrastructure works.
7. The position of the **retaining wall/debris flow barrier** needs to be optimised based on the energy gained by the flowing debris before hitting the wall and after overtopping the wall. In every retaining wall placement, the maximum retainment was observed for finer particles, and this retainment decreases with an increase in the size of particles, with the least fraction being for large size boulders. This limits the utility of the wall in case of debris flow consisting of mainly boulders.

8.2 Future Scope of work

1. This work can guide the formulation of hazard charts for other lithologies and regions affected by slope stability problems.
2. More samples can be collected from sites and tested to improve the reliability of the probabilistic numerical analysis.
3. More numerical models can also be made to increase the data set for ANN analysis to increase its predicting accuracy.