Landslide Hazard Analysis Using An Infinite Slope Stability Model Approach
(A Case Study – Garibaldi At Squamish Project)

Geob 406 – Watershed Geomorphology

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15 Apr 2016

Introduction

The provincial government of British Columbia (B.C) has recently granted an environmental approved for the Garibaldi at Squamish (GAS) ski resort project (Zeidler, 2016). This project has been a controversial debate amongst environmentalists and locals, and a detailed environmental impact assessment with 40 conditions attached have been issued to be completed by the proponents (Garibaldi at Squamish Inc.) as part of the approval certificate (Government of B.C, 2016). The study area is located approximately 15km north of Squamish on Brohm Ridge, adjacent to Mount Garibaldi and the Garibaldi Provincial Park. It is located within the Garibaldi Volcanic belt, which is commonly overlain with Garibaldi-aged volcanic material such as tuff sediment (Cruden & Lu, 1992, Bovis, 1989). Fig 1 shows the boundaries of the study area, and it is obvious that the area comprises of hilly and rugged terrain which may be susceptible to mass wasting events (e.g. landslides, rockslides, etc.). This region has a history of mass wasting events, such as the rockslide and debris flow at Mount Cayley in 1984, and Mount Meager in 2010 (Guthrie et al. 2012, Cruden & Lu, 1992). Therefore, it is necessary to determine if future developments are located within zones of potential landslides.

Understanding the risks of landslides is essential for future project developments. Unfortunately, there is a lack of study in the current environmental impact assessments of the project. Therefore, this study will utilize a simple infinite slope model to access potential landslide areas. I will be using a Digital Elevation Model (DEM) of the study area that is acquired from GeoBase's Canadian Digital Elevation Data (CDED) for my analysis. Together with the use of Geographic Information System (GIS) and its analytical tools, I will produce maps to better illustrate the potential landslide areas and advise on future development of the project. This will provide some useful recommendations for the proponents and the provincial government in their decision making when it comes to future development within the area. I will also analyse some uncertainties that are associated with the study - such as the influence of cell size and different soil parameters (e.g. soil thickness, relative saturation, etc.) on the results of the predictions - by performing a random analysis and sensitivity analysis. Last but not least, I will validate the results of the slope stability model by comparing it with aerial photographs.

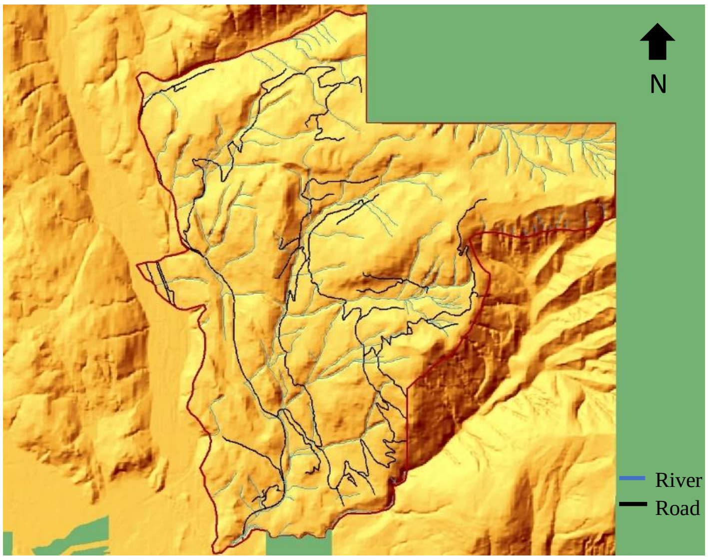

Fig. 1. GIS Hillshade image of the study area

Methodology

Slope Stability Model

In order to predict the unstable areas, I will rely on the use of a simple infinite slope stability model to calculate the Factor of Safety (FS) value for individual cells of the acquired DEM. The use of a simple infinite slope stability model has been proven to be effective in accessing stability of slopes from previous studies (e.g. Loughlin, 1974, Montgomery et al. 1994, Wu & Sidle, 1995, Zaitchik et al. 2003). A simple physical slope model is effective and can be easily applied to different study sites, unlike a multi-variate statistical analysis (Montgomery & Dietrich, 1994, Zaitchik et al. 2003). However, it must be considered that the use of a hypothetical stability model greatly over simplifies the situations and conditions of real-life scenarios. The infinite slope model incorporates a number of assumptions. It assumes a constant slope of unlimited extend with constant conditions and constant soil properties (Loughlin, 1974). It also assumes that the failure plane and ground water flow is parallel to the slope (Loughlin, 1974, Montgomery & Dietrich, 1994). This does not reflect the non-uniform conditions of natural slopes, which is why we have to take into consideration the errors and uncertainties that are coupled with the model.

$$\text{Factor of Safety (FS)} = \frac{C + C_a + (\sigma_n - \upsilon) \times \text{TAN}(\Phi) \quad \text{(Strength)}}{\sigma_g \times \text{SIN}(\beta) \quad \text{(Stress)}} \qquad (1)$$

The model evaluates slope stability and its potential of failure depending on the ratio of soil strength and shear stress acting on the soil. Soil strength and it's resistance to failure is calculated based on the Mohr-Coulomb's law. It is expressed as a strength ratio in equation (1), where C = cohesion, σ_n = normal stress, υ = pore pressure, and Φ = peak friction angle. C_a refers to apparent cohesion, which is due to the effects of root strength from vegetation (Loughlin, 1974). Shear stress is defined by vertical stress (σ_g) and the SIN of slope angle (β). If the ratio of strength and stress is less than 1 (i.e. FS < 1), then the specific plot of land is considered to be unstable or prone to landslides. Equation (1) will provide the framework of how I access the risks of landslides in the study area. In keeping with Wu & Sidle (1995), I assumed that all unstable elements (FS < 1) totally mobilized into debris flows.

$$\sigma_n = \sigma_g \cdot \text{Cos}(\beta) \qquad (2)$$

$$\upsilon = \gamma_w \cdot d \cdot m \cdot \text{Cos}(\beta) \qquad (3)$$

$$\gamma_b = m \cdot (\gamma_{sat}) + (1 - m) \cdot (\gamma_{unsat}) \qquad (4)$$

$$\sigma_g = \gamma_b \cdot d \cdot \text{Cos}(\beta) \qquad (5)$$

$$d = Z \cdot \text{Cos}(\beta) \qquad (6)$$

Equation (2) and (3) are used to determine σ_n and υ, where γ_w = bulk unit weight of water, d = soil depth, and m = relative saturation of soil (expressed as 0 – 1). Equation (4) calculates the bulk field unit weight of soil, where γ_{sat} = saturated unit weight of soil, and γ_{unsat} = unsaturated unit weight of soil. Soil depth (d) can be calculated using equation (6), where Z refers to the relative thickness of soil. Therefore, equations (1) to (6) forms the basis of the simple slope stability model which I will use in my GIS analysis. Because I do not have adequate data on the hydrology and rainfall of the area, these factors were not taken into consideration for this particular model.

Soil Properties

Soil properties and constants were used based on previous studies done in similar regions such as southwest British Columbia, (Loughlin, 1974), Mount Cayley (Cruden et al. 1992), and Mount Meager (Guthrie et al. 2012). These assumptions were made due to the lack of field data (e.g. soil samples) and studies done within the study area. Based on research done by Loughlin (1974), γ_{sat} is assumed to be 17kN/m^3, and γ_{unsat} is assumed to be 12 kN/m^3. Therefore, using equation (4) I am able to calculate γ_b which is 14.5 kN/m^3, assuming that relative saturation of the soil is 0.5. Loughlin (1974) also suggested a C_a value of 2kPa due to root strength. C is assumed to be 0 since the area is assumed to be mostly overlain by tuff sediment, which is considered to be cohesionless (Cruden & Lu, 1992). Z is assumed to be relatively uniform for the ease of computation and calculations, and is averaged to 2m based on the studies by Cruden et al. (1992), Guthrie et al. (2012), and Loughlin (1974). Last but not least, β is obtained using the GIS raster surface slope tool to produce a raster map of slope angles from the DEM (fig. 3). After determining all the relevant soil parameters and variables, I am then able to start my analysis using GIS.

GIS Analysis

The DEM used has an original cell size of 18.65m by 18.65m. The DEM is used to create a slope raster, and also a raster for the different equations of the slope stability model. Using GIS raster calculator, I am able to compute the slope stability model by calculating equations (1) to (6). Each cell would be attributed with a unique FS value which tells us whether it is predicted to be unstable or stable.

Results

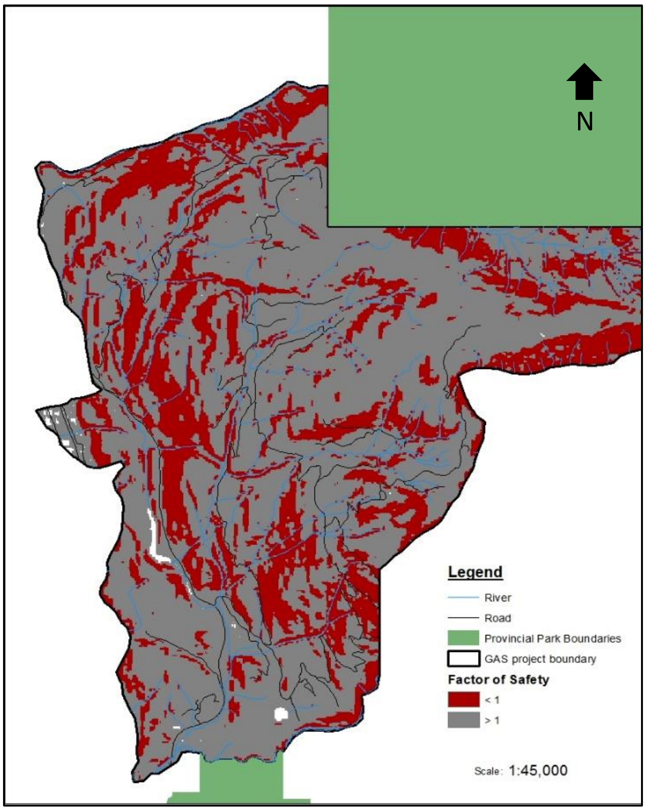

Fig. 2. Factor of Safety map for study area

Fig. 2 shows the results of the model after computing equation (1), where red delineates areas that are considered to be unstable or prone to landslides. Approximately 30% of the study area is predicted to be unstable based on the slope stability model. Some of predicted unstable areas overlap with existing road networks, which is considered to be a potential landslide hazard. Roads within those area might be affected during mass wasting events, which might result in economic or even human life loss. Therefore, it is important to take into consideration when planning for future development of the ski resort, and how road networks should be built. When compared to fig. 3, it is obvious that most of the unstable areas corresponds with areas with high slope of more than 40°. This makes sense as a higher slope angle would increase the tangential stress acting on the soil, which reduces the FS ratio.

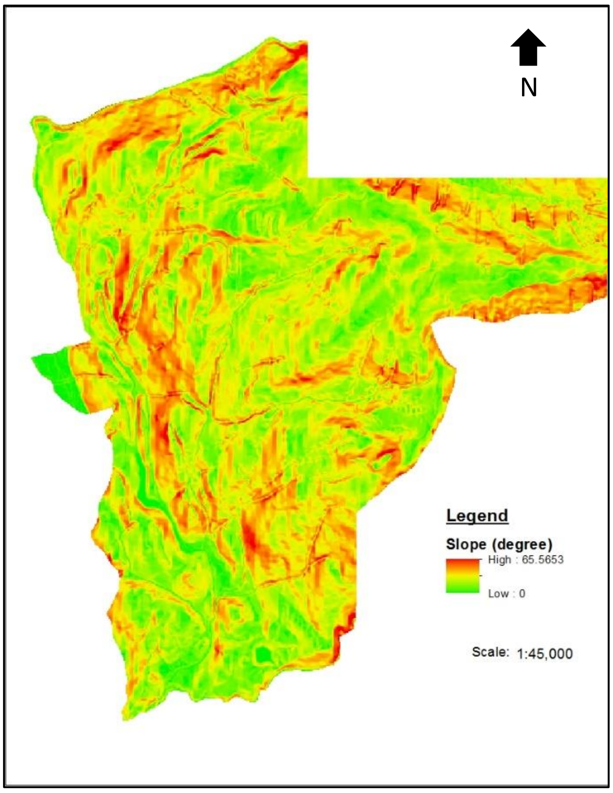

Fig. 3. Map showing slope angles of study area

Random analysis

Because of the various assumptions by the simple slope stability model as mentioned above, it is important to understand how the model would work under non-uniform conditions. This will better represent the real-world scenarios and conditions of natural slopes. Therefore, I used a random analysis approach to introduce 'randomness' or variability to the uniform soil properties. The first analysis done was to determine the effects of uneven soil thickness across the study area, assuming all other variables remained constant. I varied Z across the study area between 1m to 4m, instead of the constant 2m used under controlled settings. This is done using GIS, by creating different random polygons with the different soil thickness values and converting them into raster data. Fig. 4 shows the result of the analysis.

The total area that are considered to be unstable increases by approximately 2% under non-uniform conditions for soil thickness. This suggest that assuming constant Z in such studies might underestimate the areas that predicted to be unstable.

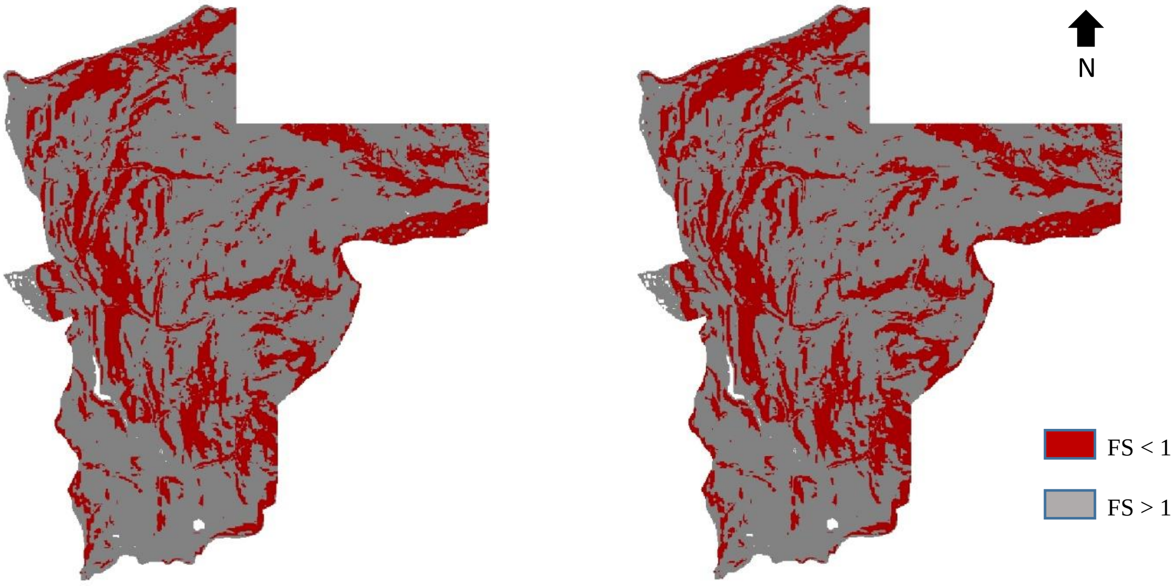

Fig. 4. Unstable areas for constant soil thickness of 2m (left) and non-uniform soil thickness from 1m to 4m (right)

The second analysis done was to determine the effects of varying C_a between 1kPa to 3kPa, since vegetation cover might not be uniform throughout the area due to clear-cut activities, etc. After varying C_a throughout the area, the total unstable area decreases by 2.5% as compared to the control constant conditions (fig. 5). Areas with higher C_a will result in a higher soil strength due to equation (1), and will thus increase FS and stability of the soil. This is important as it would determine the effects of clearing existing vegetation for the purpose of the developmental project. It is important to have more accurate data on vegetation cover within the study area, in order to have better predictions by the slope stability model.

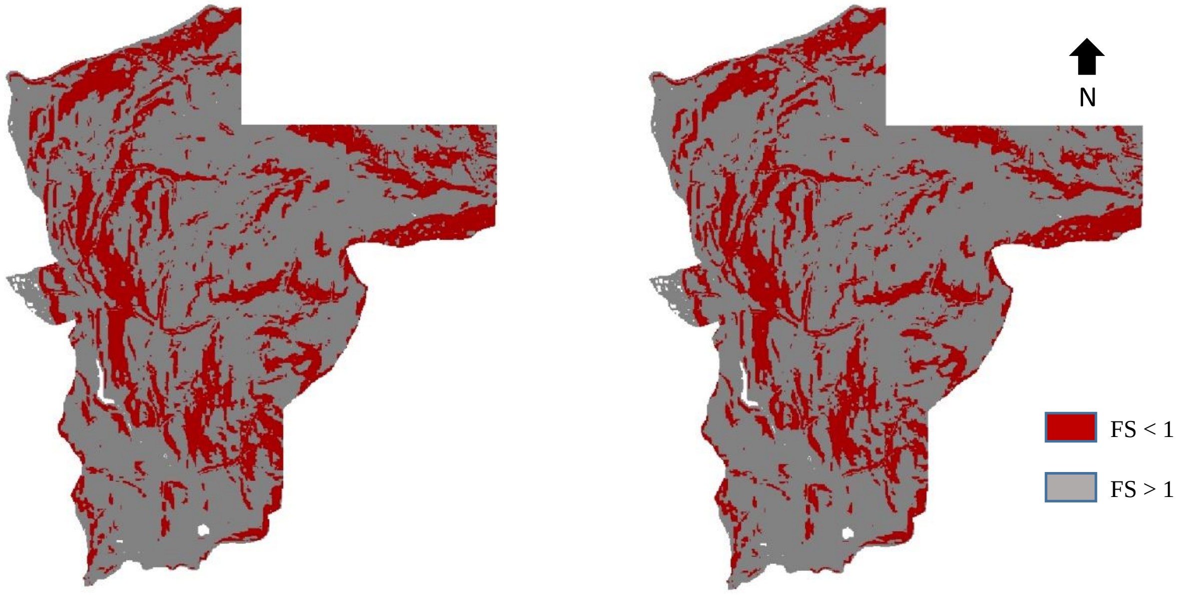

Fig. 5. Unstable areas for constant apparent cohesion (left) and non-uniform apparent cohesion from 1kPa to 3kPa (right)

In order to determine the effects of m, I also did an analysis to determine how a change in m would affect the results of the model. Cruden & Lu (1992) suggest that tuff sediment is relatively low dry density, and sufficient water may accumulate on the tuff layer to fully saturate it. If we assume that the soil is fully saturated and that m is equal to 1, the areas with FS < 1 increases drastically (fig. 6). It is expected of the areas of instability to increase with soil saturation, but the results exceeded my expectations. This suggest that it is essential to know the how saturated is the soil, as it has a huge impact on the model predictions. The study by Loughlin (1974) also suggest that the stability of the slopes are heavily dependent on the effects of root strength on apparent cohesion of the soil during storm periods when the soils are saturated. Therefore, it would benefit to have more detailed soil samples from the study area, as well as hydrology and rainfall data.

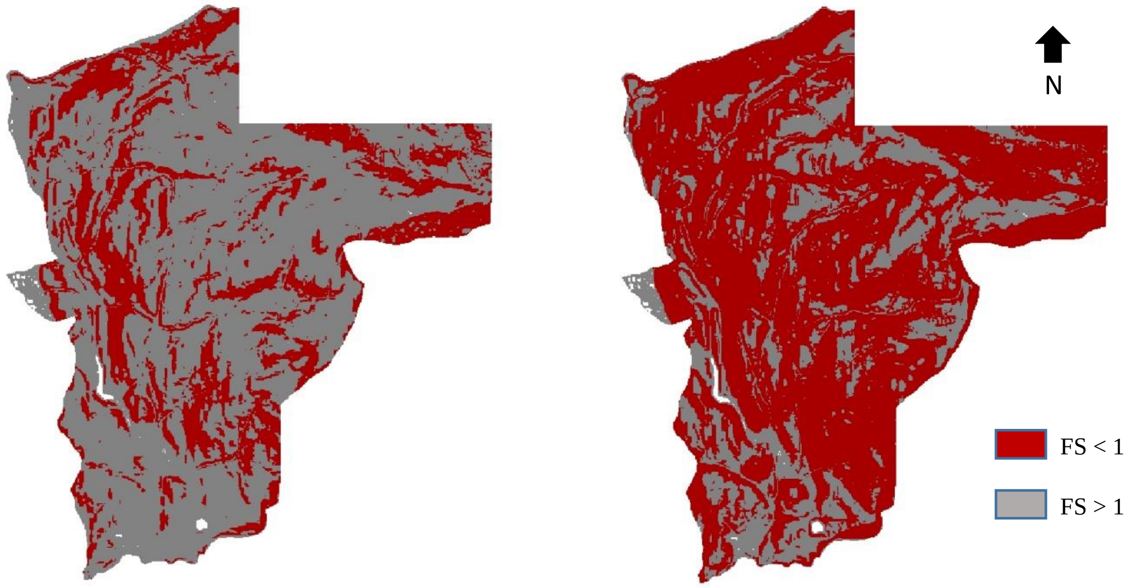

Fig. 6. Unstable areas for relative saturation of 0.5 (left), and 1 (right)

Sensitivity Analysis

The purpose of a sensitivity analysis is to determine the errors and uncertainties associated with the study. To understand how the cell size in different DEMs might affect the results of the model predictions and the study, I performed a sensitivity analysis by resampling and changing the cell size for the original DEM to 35m and 50m. Looking at fig. 7, we can see that the total area for FS < 1 decreases as cell size increases. The number of pixels with FS < 1 reduces when we increase the cell size of the DEM. This is most likely due to the reduction in higher slope angles when the DEM is resampled. This supports the arguments made by Paulin et al. (2010), as they showed that the number of landslide pixels decreases as the cell size is increased. Therefore, increasing the cell size of the DEM will result in the loss of cartographic representation for landslides.

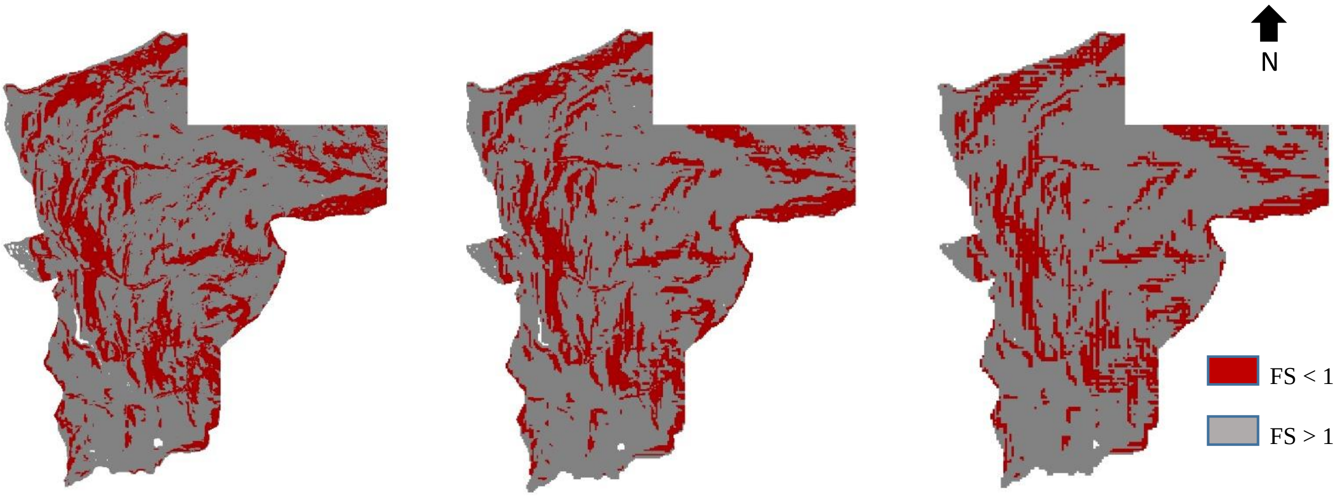

Fig. 7. Unstable areas for 18.65m (left), 35m (middle), and 50m (right).

Validation

To validate the results of the slope stability model, I relied on aerial photography records from UBC department of geography's Geographic Information Centre (GIC) to detect any history of landslide scars within the area. I focused on a specific region (Brohm ridge) within the project boundary, due to a limitation of data (fig. 8). I used two sets of air photos that were taken in 1994 and 2005 respectively. The air photos were at a scale of 1:15,000. Areas that have no vegetation cover (e.g. clear cut, bare ground) appears to have some mass wasting activity which corresponds with the model predictions. There are some signs of debris flow on barren grounds, and are usually adjacent to tributaries or streams. However, areas with dense mature vegetation cover are difficult to detect any mass wasting activity below the canopy cover.

There were some limitations to the validation, primarily because I have no experience in detecting landslide scars. It is also difficult to distinguish amongst different landscape features in a panchromatic (black and white) air photo. The available air photos for the region were also limited. Therefore, the validation process might have some degree of error and uncertainty. Overall, there seems to be little correlation between the model predictions and the air photos. This might have to do with the lack of consideration for rainfall and hydrology in the simple slope stability model. Therefore, it is beneficial to incorporate more complex models such as the hydrologic model TOPOG as suggested by Montgomery & Dietrich (1994).

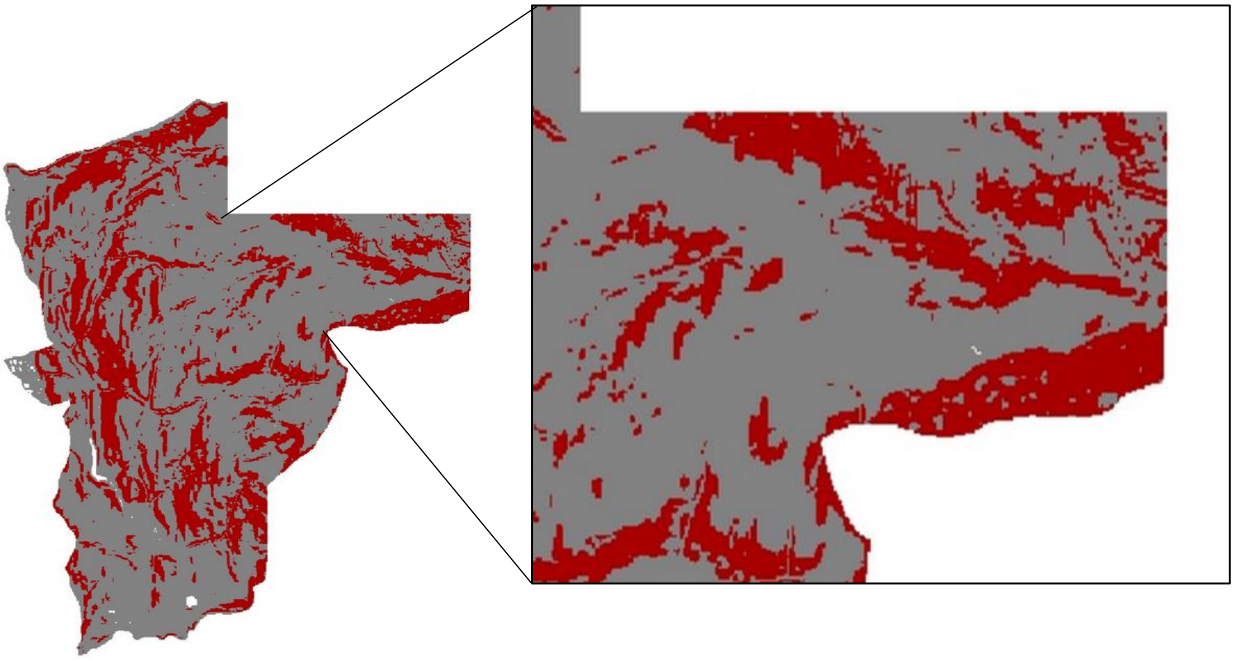

Fig. 8. Area of comparison with air photos

Limitations

There are many uncertainties in this study due to the lack of relevant soil data, and assumptions for the many unknown parameters such as soil saturation. Most of the assumptions and soil properties used in this study were based on previous literature and studies done in regions with similar geological characteristics. Therefore, the results from this study might not accurately represent the actual conditions of the study area. This study also did not account for the effects of snow and ice accumulation on slopes, which may affect the stability of slopes due to increase weight or snowmelt runoff. Future studies should consider to analyse the effects of snow on slope stability, since the project is proposed to be an all-year-round ski resort.

Conclusion

The benefits of using slope stability models have been highlighted by previous studies (Loughlin, 1974, Wu & Sidle, 1995, Montgomery & Dietrich, 1994, Zaitchik et al. 2003). A simple slope stability model works best when conditions are more or less uniform and homogenous, where soil properties are assumed to be constant throughout. They are useful tools to study the physical behaviours of slopes, especially with the incorporation of more complex models and also larger inputs of data (e.g. soil, hydrology) and information. This would increase the accuracy of the models and its predictions of slope instability and the susceptibility of landslides.

In the absence of anthropogenic disturbance or geological faults, the relative stability of a slope is mostly controlled by local slope gradient and the degree of soil saturation (Zaitchik et al. 2003). This is evident when comparing fig. 2 and fig. 3. Future development within the project boundary should avoid areas with slopes of more than 40^{o}, in order to ensure any damage to infrastructure from mass wasting events. Road network that runs through unstable areas should have appropriate signage. As mentioned by Loughlin (1974) and supported by the random analysis of this study, vegetation and the effects of root strength can greatly affect the stability of slopes. Therefore, it is not advisable for any development to remove mature vegetation (via clear-cut) from slopes with high gradients, as it would increase the slope's susceptibility to landslides. Soil saturation has a great impact on soil stability, as seen in fig. 6. Therefore, it is important to prevent any changes that would induce saturation of steep slopes within the study area. Future development should avoid diverting surface drainage to gully heads or steep slopes, which will increase the probability of landslides due to the decrease in FS.

Acknowledgements

Special thanks to Carles Ferrer-Boix for taking the time off and providing all the unconditional help with the formulation and application of the slope stability model. Also to Sally Hermansen for providing background information about the Garibaldi at Squamish project and the relevant GIS data for this study.

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