AN INTEGRATED GIS – GEOTECHNICS APPROACH TO LANDSLIDE ANALYSIS: APPLICATION TO MOUNTAIN ROCK SLOPE DEFORMATIONS

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ABSTRACT
The analysis of large landslides is often difficult due to the complexity of natural materials. Detailed research studies quickly become exercises in data management. A “Landslide Research Toolbox” is currently being investigated which combines digital field data collection, geographical information systems and geotechnical analysis. Focused on the site scale, this integrated set of techniques provides several benefits to the potential user. To illustrate these tools in practice a case study of the analysis of sackungen (or bedrock linears) at Mount Mercer, British Columbia is presented. Located in the Chilliwack River Valley of south western British Columbia, Mount Mercer is composed mainly of marine sedimentary rocks. At Mount Mercer several features typically associated with extensive slope deformation (tension cracks, ridge top trenches, and anti-scarps) have been identified. Field mapping of the geotechnical bedrock properties is combined with terrain analysis and geomechanical modelling to understand the genesis of the features.

RÉSUMÉ
L’analyse des déformations gravitaires des versants rocheux est souvent difficile due à la complexité des materiaux naturels. Les projects d’étude de terrain detaillées deviennent rapidements des exercices de gestion de données. Le developement d’une “boite à outils” de techniques specifique à l’étude des déformations gravitaires des versants rocheux est presentement en cours. Celle-ci combine la collecte digital de données de terrain digitale, les systèmes d’information géographique et l’analyse géotechnique. L’accent est mis sur l’échelle de l’étude de terrain, cet ensemble de techniques offre plusieurs benefices à l’utilisateur. Pour illustrer ces outils dans un context pratique, une analyse des sackungen (ou des linéaire de socle rocheux) présent au Mont Mercer (Colombie-Britanique) est présentée. Situé dans la vallée de la Rivière Chilliwack au sud-ouest de la Colombie-Britanique, le Mont Mercer se compose principalement de roches sédimentaires marines. Plusieurs traits morphologiques typiquement liés à la deformation prononcer des versants rocheux (fissures de tension, arrête en tranché, contrepente) ont été identifiés au Mont Mercer. L’étude de terrain des proprietés géotechniques du socle rocheux est combiné avec géomorphologie et modélisation géomechanique pour comprendre la genèse de ces traits morphologiques.

1. INTRODUCTION

Integrating data management and manipulation techniques provided by modern geographical information systems (GIS) with standardized site investigation methods results in a powerful research system. The GIS is multi-purpose tool which can serve as the hub of a suite of integrated mapping and analysis tools. The spatially enabled relational database, at the core of the GIS, provides data storage and management capabilities. The increasing computational speed of personal computers has allowed the development of powerful 2D and 3D visualization tools for spatial data. Digital data collection allows rapid updating of the GIS as well as increased quality of collected data. Rapid extraction of data from the database for engineering analysis is easily accomplished by the querying and manipulation tools available to the desktop GIS user. Data limited problems benefit from this approach as all of the available data can be leveraged to their full potential.

1.1 Previous Applications

Previous uses of GIS for geotechnical purposes have focused on the regional or multi-site scale. Dermentzopoulos and Katsaridis (2002) describe data management and GIS for urban planning projects in Greece. A GIS developed to assist the construction of MRT lines in Singapore is reviewed by Kimmance et al. (1999). GIS as a data source for geotechnical analysis in forested terrain of the Pacific Northwest has been demonstrated by Miller (1995). Integrating geotechnical mapping and analysis with GIS applications in general has been reviewed by Rengers et al. (2002). Aste and Badji (1996) describe a tightly integrated system of software programs for slope engineering analysis.

2. A LANDSLIDE RESEARCH TOOLBOX

The goal of the “Landslide Research Toolbox” (LRT) is the collection, management, and analysis of data at the local site scale. These goals are accomplished by the integration of digital data collection / mapping systems, GIS, and geomechanical modelling / analysis packages. Currently, the components of the LRT are at the “first level integration” (“Separate but equal”) described by Ehlers et al. (1989). Each component functions separately, but data is easily moved from one application to another. This loose integration provides a flexibility that allows the user to use their preferred software packages for each component of the LRT. As well, flexibility in hardware choices can also be realized.

2.1 Digital Data Collection and Storage

Following the examples of the Geological Survey of Canada (GSC) and the Yukon Geological Survey (YGS) (Lipovsky et al., 2003) a digital field data collection system has been created by combining consumer level handheld computers with mobile database software. Hardware requirements for the data collection system are minimal (replaceable battery, removable media support, and moderate screen resolution). Currently available handheld computers are more than adequate. Several mobile database software packages exist each with its own positive and negative features. The ability to "synch" with a desktop or GIS database is the main requirement for choosing a mobile database product. A custom data model for geotechnical and terrain data is required for the basis of the both the mobile database and the GIS database.

The SFU_Geotech data model combines elements of the B.C. Terrain Classification system (Howes and Kenk, 1997) with standard geotechnical site investigation observations (discontinuity survey, rock mass classification, field photos, testing results). Designed as a series of relational tables, the data model can be implemented in any common relational database. The general structure of the data model (Figure 1) breaks up the constituent classification systems (B.C. Terrain Classification, NGI Q, GSI, RMR) into data tables based on subjects under observation. The data required by each classification system can be simply extracted from the database using standard queries. The database on the handheld computer is mirrored by the database on the desktop PC.

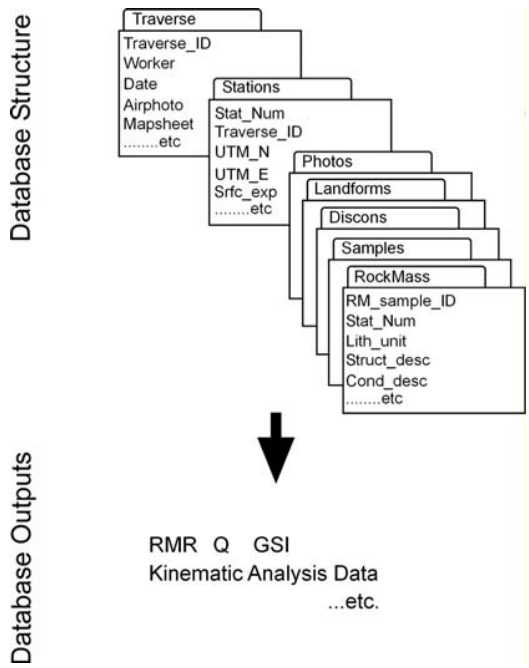

Figure 1: Data model structure for SFU_Geotech with standard database outputs

2.2 Data Manipulation and Visualization

The desktop database provides data storage and manipulation to the user or group. Rock mass classifications can be completed and displayed rapidly using SFU_Geotech. Once the field observations of discontinuities (spacing, roughness, weathering, etc.) and bedrock (UCS estimate, weathering, structure, etc.) have been made, simple queries can be used to extract the appropriate observations for the Q or RMR classifications from the database. Automated calculations for the final index value of each classification method are completed for every station. As each station in SFU_Geotech has a spatial location attached to it (typically UTM from GPS) the classification results can be displayed graphically in the GIS. If sampling density is high enough, gridded / contoured representations of field data values are possible.

The advantages of basic map production have already been realized in projects using GIS for regional studies. Additional visual outputs (based on Digital Elevation Models) useful for site scale investigations are available including:

- Hill Shades
- Slope Maps
- Photo Overlays

Hillshade images are derived from digital elevation (DEMs) data by calculating the shadow intensity expected for each DEM grid cell based on the sun position. The highlights and shadows produced increase the visibility of terrain features in the study area. Slope maps are derived by an algorithm which compares elevation differences across cells in the DEM. The slope map provides a colour coded output for rapid illustration of slope changes over the site. Rectified scanned aerial photographs or satellite images can be "draped" over the DEM to produce photo realistic terrain models. Viewing angles not even possible from a helicopter can be used to review the site and may lead to significant improvements in the interpretation of landforms.

2.3 Modelling and Analysis

The diverse problems encountered in researching large landslides (difficult terrain, lack of sub-surface data) require a range of tools. Any geotechnical analysis or modelling package can be included in the LRT due to the nature of the component integration. The researcher is free to use their engineering judgement in regards to the best analysis tool for any problem. Cross sections, discontinuity data and rock mass properties can be rapidly extracted from the GIS using visual tools for specific areas of interest on the slope.

2.4 Work Flow

Within the "Landslide Research Toolbox" framework, the GIS is a central hub for the basic research work flow (Figure 2). The initial reconnaissance of the study area is completed with available maps and aerial photographs.

These data may require conversion to a digital format to be imported into the GIS. Digital elevation maps and 3D visualization may also be useful at this stage. The field mapping and site investigation utilize the digital data collection system to a significant degree. Once all of the available data has been aggregated in the GIS, conceptual models of failure modes or processes can be constructed with the aid of data visualization routines from the GIS. The conceptual models are tested with geomechanical modelling software using topography and rock properties representative of the field data extracted from the GIS. These tests may lead to improvements or modifications of the conceptual model; they may also lead to information on where to focus additional field work.

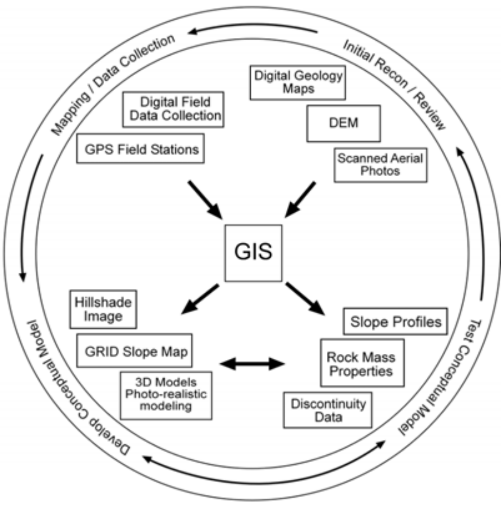

Figure 2: Work flow and integration of components of the "Landside Research Toolbox"

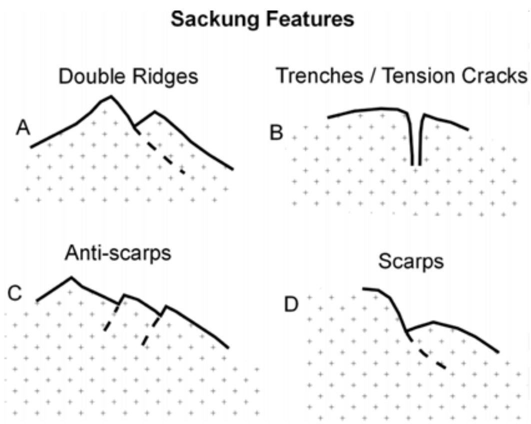

Figure 3: Landforms associated with sackung. Range in vertical displacements: A and D: 10's to 100's of metres, B and C: 1 - 10's of metres. All of the features can have lateral extents in the 1000's of metres.

3. MOUNT MERCER CASE STUDY

3.1 Background

“Sackung” (Zischinsky, 1969) or “bedrock linears” (Bovis and Evans, 1996) have been identified in most mountainous regions of North America and Europe. Examples of these features are ridge top trenches (Jahn, 1964), uphill facing (or “anti-slope”) scarps (McCalpin and Irvine, 1995), normal scarps, and tension cracks (Figure 3). Typically occurring in combinations of apparently related landforms, their genesis is controversial. Many of these landforms are laterally extensive on the kilometre scale. Some previous authors have surmised that these landforms are surficial indicators for deep-seated gravitational displacements within the rock mass of the mountain slopes.

3.2 Study Area

Mount Mercer is located in the Chilliwack River Valley of British Columbia (Figure 4). Significant sackung features (scarps, ridge-top trenches, anti-scarps) can be seen from aerial photographs. One of several unstable slopes in the Chilliwack River Valley (Thomson, 1998), the case study of Mount Mercer provides a good example of the application of the “Landslide Research Toolbox.”

The sedimentary and volcanic rocks in the Chilliwack River Valley (Figure 4) have undergone two phases of tectonic folding and faulting (Monger, 1966). The initial folding was to the north-west and resulted in recumbent isoclinal folds with hinge surfaces trending north-west. Accompanying the folds are low angle thrust faults, also trending to the north-west (Monger, 1966; Thomson, 1998). The Chilliwack River Valley has been subject to glacial ice from both valley and alpine sources. Two main sources of valley ice are responsible for much of the deposited material in the trunk valley: The Fraser Valley Ice lobe and the Chilliwack Valley glacier (Saunders et al., 1987). The Fraser Valley Ice lobe was located at the western margin of the valley and at times completely blocked the mouth. All of the terrain in the Chilliwack River Valley has been modified by glacial erosion processes.

The initial review of Mount Mercer was undertaken through aerial photograph interpretation. The aerial photograph reconnaissance revealed discrete sackung features occurring over the ~4 km length of the Mount Mercer ridge line. Most of the features were concentrated on the ridge line and upper portion of the main south-east aspect slope of Mount Mercer. To extend the usefulness of the aerial photographs, they were scanned and rectified. Once draped over a digital elevation model (DEM) in the GIS, additional visualizations (different lighting and viewing angles) could be created which significantly increased the value of the photographic interpretation. A structural cross section through part of the Chilliwack River Valley by Monger (1966) passes through Mount Mercer at an oblique angle to the fall line of the main ridge slope. This provided some insight into the possible structural geology of the ridge.

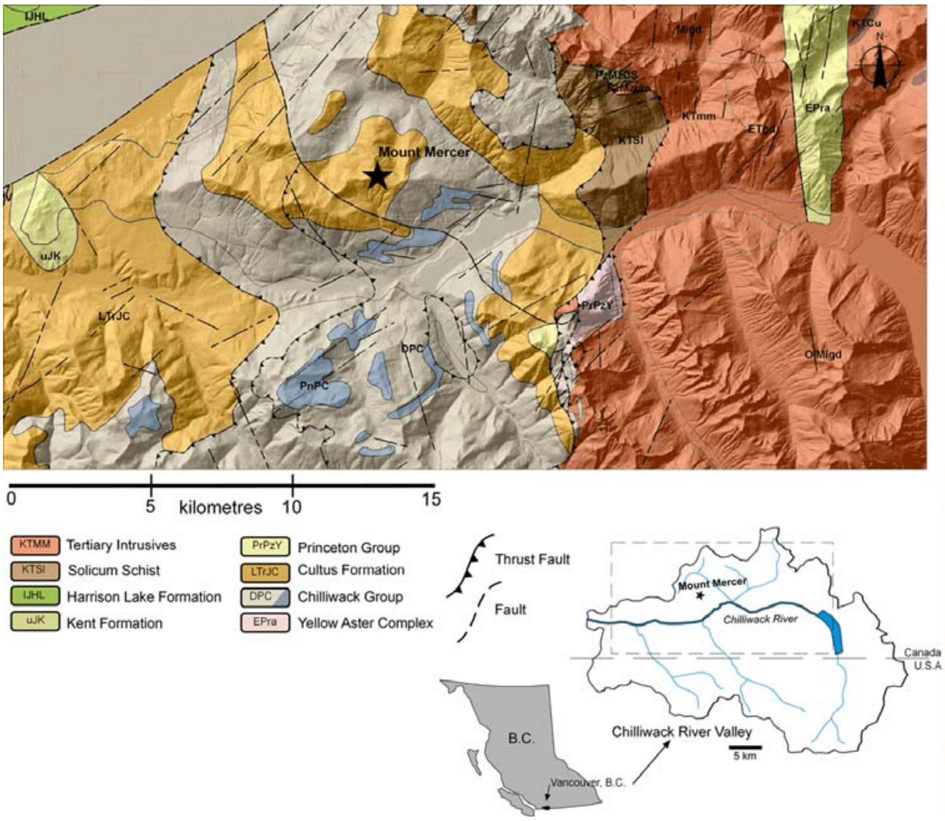

Figure 4: Location and regional geology of the Chilliwack River Valley.

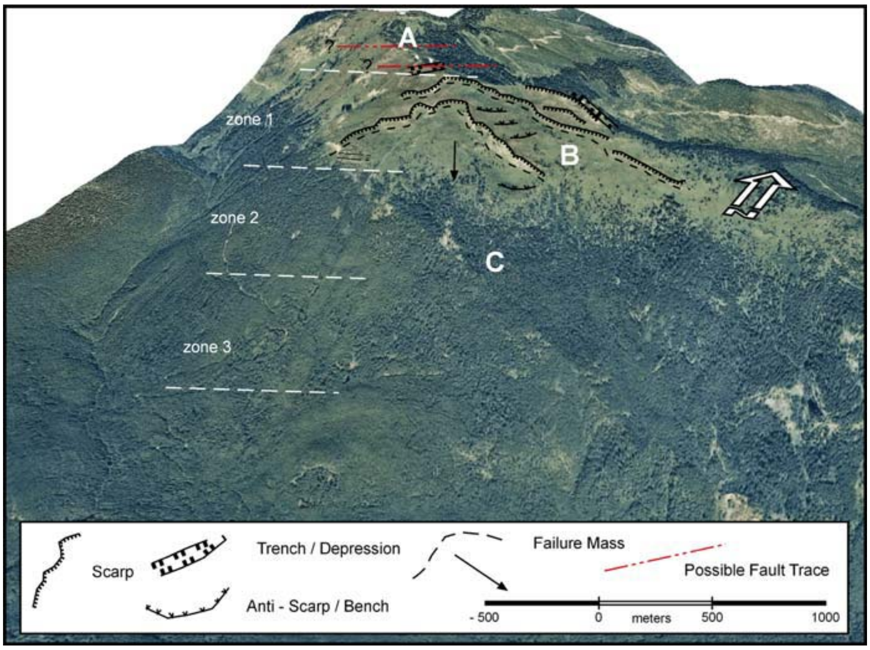

Figure 5: Landforms and "slope zones" mapped on a draped aerial photograph of the main slope of Mount Mercer

3.3 Engineering and Geomorphological Mapping

Geomorphic and geotechnical observations made in the field were collected by handheld computer into a database based on the SFU_Geotech data model. Trenches on the ridge line (A), scarps / anti-scraps on the upper slope (B), and benches on the mid-slope (C) were mapped on the main south-east aspect slope of Mount Mercer (Figure 5) These mapped landforms were added to the GIS by both digitally mapping onto scanned aerial photos and using GPS coordinates. Field photographs of these landforms were attached to each mapped representation in the GIS. In the vicinity of these features, four geotechnical units were mapped (Table 1). Generally, the rocks at Mount Mercer are closely jointed (< 0.5 metre spacing) volcanically derived sedimentary rocks. GSI and Q were estimated for the rock mass at each field station. Intact uniaxial compressive strength for the rocks mapped was estimated from Schmidt hammer tests in the field and laboratory point load testing on samples.

Table 1: Mean UCS, GSI, and Q values for geotechnical units mapped at Mount Mercer.

Unit	Rock Description	Intact UCS (MPa)	GSI	Q
A	Interbedded fine sandstone with siltstone and shale	100 - 110	30 - 50	1 - 10
B1	Foliated Basalt	140 - 160	25 - 45	0.1 - 1
B2	Tuff (Ash + Volcanic Fragments)	190 - 210	60 - 70	1 - 10
B3	Massive Limestone / Cherty Limestone	90 - 100	50 - 70	1 - 10

3.4 Conceptual Model Development

From the field relations of the mapped landforms, it was apparent that the sackung features of the main south-east aspect slope of Mount Mercer could be explained by large, potentially deep-seated mass movement. Toppling is an often suggested mode of failure leading to sackung features (Bovis and Stewart, 1998; Bovis and Evans, 1996). Following the suggested technique of Bovis and Evans (1996), kinematic analysis of discontinuities mapped in relatively undisturbed zones was carried out.

Field stations in the undisturbed zones were selected in the GIS and the discontinuity data (orientation, condition) for each station was queried from the database. The data was exported to the stereonet software package, DIPS (Rocscience, 1999), for analysis. Kinematic tests for toppling and sliding showed that both failure modes were inadmissible for the main south-east aspect slope of Mount Mercer. Lacking a simple failure mode, complex failure modes based on the geomorphological observations of the slope were considered.

The overall slope could be broken down into three zones based on slope angle (Figure 6)

- an upper steep section (1)
- a low angle mid slope (2)
- and a steep slope toe (3)

The general morphology of the slope combined with the landforms in each "slope zone" gave the impression of a rotational mechanism. From these geomorphic clues a failure mode of rock slumping was investigated.

Described in detail by Kieffer (1998), rock slumping occurs as blocks with a low base to height ratio slide and back-rotate along shallow dipping daylighting discontinuities. The resultant morphology is similar to that of a soil slump. Kieffer (1998) describes four characteristic landform sets associated with rock slumping:

- A steep, well defined head scarp (s)
- A series of stepped scarps in the upper slope
- Mid-slope topographic benches
- A steep toe

These features are representative of landforms observed at Mount Mercer (Figure 5).

The kinematic requirements of rock slumping are an over dip cataclinal (terminology after Cruden, 1989) joint set and a shallow dipping daylighting joint set. Reviewing the discontinuity data for Mount Mercer, the required cataclinal joint set exists (Figure 7). A persistent shallow dipping daylighting joint set is not seen in the collected data. From the structural geology cross section (Monger, 1966), both thrust faults and extensive isoclinal, recumbent folding occur near the possible toe of the failure. It is therefore possible that a sub-horizontal persistent fault / fault damage zone or "surface" of weakness exists within the rock slope mass. Without sub-surface borehole investigations, such a zone can only be inferred as a cause of slumping.

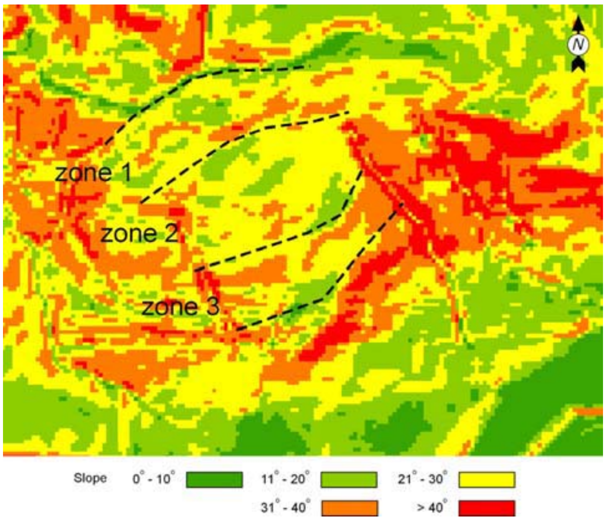

Figure 6: Slope map derived from the DEM of Mount Mercer. Three "slope zones" are identified from the slope map.

3.5 Conceptual Model Testing

The possibility of rock slumping at Mount Mercer was tested through geomechanical numerical modelling. Slope cross sections were extracted from the GIS (Figure 8). Rock properties for the units of interest were developed from data queried from the GIS database and the Hoek-Brown failure criterion. The modelling was completed using the distinct element code UDEC (HCItasca, 2002) (Figure 8). Modelling focused on investigating the kinematics of rock slumping and observing the resultant ground surface morphology. A similar study was undertaken by Bovis and Stewart (1998) with regard to toppling and the development of sackung features. The results of the UDEC model showed rock slumping as a feasible mechanism over a range of block base to height ratios. The topography produced by rock slumping in UDEC was representative of the types of landforms observed at Mount Mercer. In addition, the presence of either a low angle damage zone or a continuous plane would facilitate rock slumping.

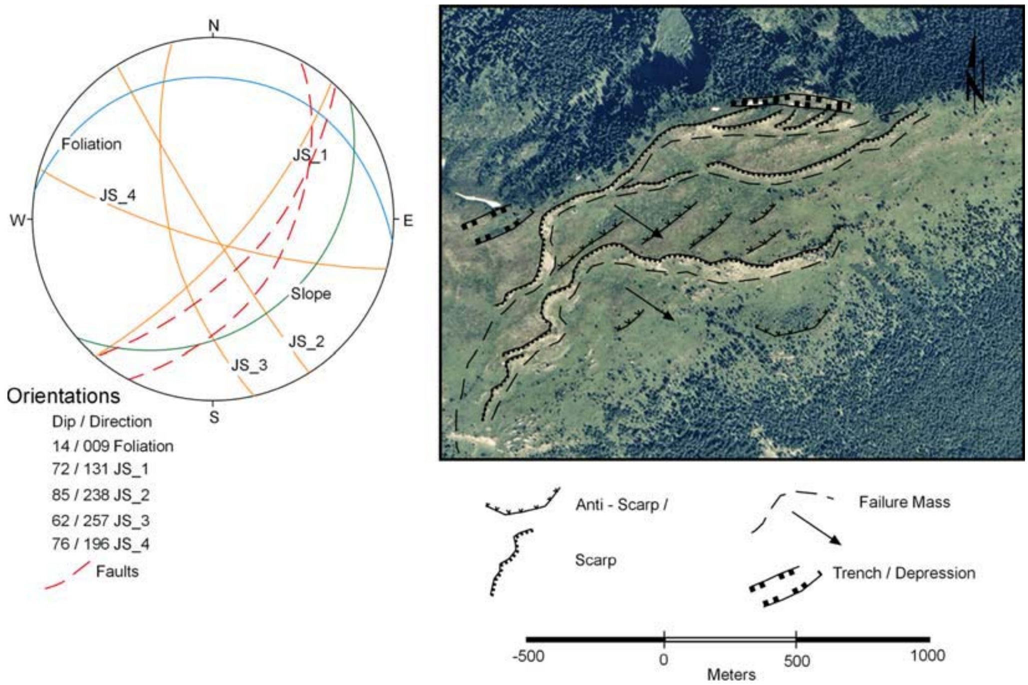

Figure 7: Mean joint orientations and faults compared to landforms orientations at the ridge line. Cataclinal joints are oriented similar to faults mapped at Mount Mercer.

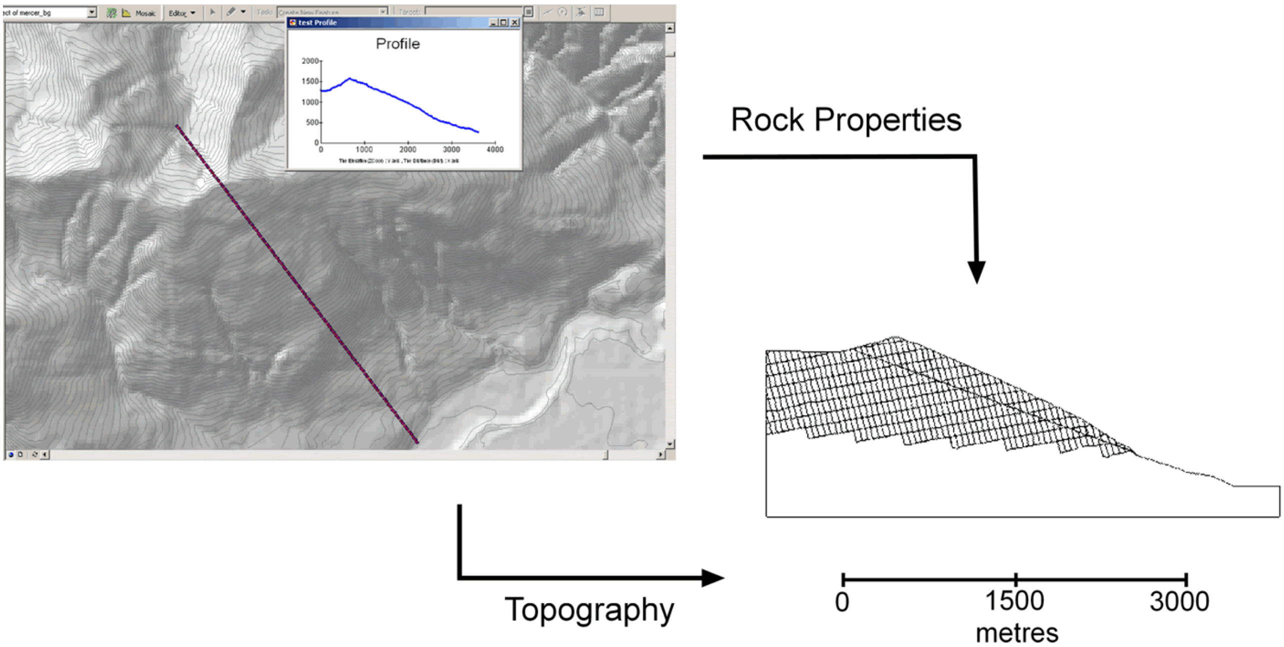

Figure 8: Data export from the GIS for use in geomechanical (UDEC) modelling.

4. SUMMARY

The potential applications of each component of the loosely integrated "Landslide Research Toolbox" are summarized in table 2. Each component allows certain benefits; when used together increases in the quality of data collected during a study can be realized. The additional visualization tools available through the GIS significantly improve conceptual model development. Overall, the LRT approach allows the optimization of available data for the problem at hand.

The Mount Mercer case study illustrates the utility of the "Landslide Research Toolbox." A new conceptual model for the development of sackung features in British Columbia is supported by data and numerical analysis. The integration of techniques allowed a new perspective on features with an uncertain and controversial origin. Although a complete answer cannot be provided without subsurface data, the usefulness of the data available is maximized through the application of the "Landslide Research Toolbox" approach.

Table 2: Summary of possible applications of the components of the "Landslide Research Toolbox"

LRT Component	Applications
Digital Data Collection	- Automated Error Checking - Standardized Data Inputs - Rapid Database updating - Spatially referenced data - In field application of geotechnical classification algorithms
Data Storage and Manipulation	- Hill shade maps - Slope and Aspect Maps - Catchment Area delineation - 3D Photo realistic model - Gridded / Contour Data Representations (Q, GSI, etc.) - Extract Profiles from DEM - Extract rock properties from database - Extract discontinuity data for Kinematic Analysis - Interactive classification algorithms
Modeling and Analysis	- Compare model topography to 3D GIS models - Compare model kinematics to geomorphology - GIS visualization of numerical model results

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REFERENCES

Aste, J.P., Badji, N. 1996. Slope Engineering Toolbox, a multi-purpose system for slope engineering problems. in Landslides, Senneset (ed.) Balkema, Rotterdam: 599 - 603

Bovis, M.J., Stewart, T. 1998. Long-term deformation of a glacially undercut rock slope, Southwest British Columbia. Proceedings - International Congress of the International Association for Engineering Geology and the Environment 8: 1267-1276

Bovis, M.J., Evans, S.G., 1996. Extensive deformations of rock slopes in southern Coast Mountains, southwest British Columbia, Canada. Engineering Geology, 44: 163 - 182

Cruden, D. 1989. Limits to Common Toppling. Candian Geotechnical Journal, 26: 737 - 742

Dermentzopoulos, T., Katsaridis, P. 1997. Engineering geological data management for urban planning using GIS: A case study from Piraeus, Greece. in Engineering Geology and the Environment, Marinos, Koukis, Tsiambaos, and Stournaras (eds.), Balkema, Rotterdam: 1225 - 1228

Ehlers, M., Edwards, G., Bedard, Y. 1989. Integration of Remote Sensing with Geographic Information Systems: A Necessary Evolution. Photogrammetric Engineering and Remote Sensing, 55(11): 1619 - 1627

HCItasca, 2002. Udec version 3.1, Minneapolis: HCItasca Consulting Group.

Howes, D.E., Kenk, E. 1997. Terrain Classification System for British Columbia (version 2) Guide Book, Ministry of Environment, Lands and Parks, Victoria, B.C.

Jahn, A., 1964. Slopes morphological features resulting from gravitation. Zeitschrift fur Geomorpholgie, Supplement Band 5: 59 - 72

Kieffer, D.S. 1998. Rock Slumping: A Compound Failure Mode of Jointed Hard Rock Slopes. PhD thesis, Civil and Environmental Engineering, UC Berkley.

Kimmance, J.P., Bradshaw, M.P., Seetoh, H.H., 1999. Geographical Information Systems (GIS) Application to Construction and Geotechnical Data Management on MRT Construction Projects in Singapore. Tunnelling and Underground Space Technology, 14(4): 469 - 479

Lipovsky, P.S., Colpron, M., Stronghill, G. and Pigage, L., 2003. GeoFIELD v.2.2 – Data management and map production for the field geologist. Yukon Geological Survey Open File 2003-8(D).

Massey, N.W.D., MacIntyre, D.G., Desjardins, P.J.,2003. Digital Map of British Columbia: Tile NM10 Southwest B.C., B.C. Ministry of Energy and Mines (BC Geological Survey), Geofile 2003-3.

McCalpin, J.P., Irvine, J.R. 1995. Sackungen at the Aspen Highlands Ski Area, Pitkin County, Colorado. Environmental & Engineering Geoscience, 1(3): 277 – 290

Miller, D.J. 1995. Coupling GIS with Physical Models to Assess Deep-Seated Landslide Hazards. Environmental & Engineering Geoscience, 1(3): 263 - 276

Monger, J.W. 1966. The Stratigraphy and Structure of the Type – Area of the Chilliwack Group, Southwestern British Columbia. UBC Geology, PhD Thesis.

Rengers N., Hack R., Huisman M., Slob S. Zigterman W. 2002 Keynote: Information technology applied to Engineering Geology. Engineering Geology for Developing Countries - Proceedings of 9th Congress of the International Association for Engineering Geology and the Environment. J. L. van Rooy and C. A. Jermy, editors: 121-143

Rocscience. 1999. DIPS User Manual. Rocscience Inc., Toronto, Ontario

Saunders, I.R., Clague, J.J., Roberts, M.C. 1987. Deglaciation of the Chilliwack River valley, British Columbia. Canadian Journal of Earth Science, 24: 915 - 923

Thomson, B. 1998. Slope failures; Chilliwack River drainage basin; a mass movement class room. Proceedings - International Congress of the International Association for Engineering Geology and the Environment 8: 1097-1101

Zischinsky, U. 1969. Uber Sackungen. Rock Mechanics, 1: 30 - 52