MULTI-SCALE CHARACTERIZATION OF ROCK MASS DISCONTINUITIES AND ROCK SLOPE GEOMETRY USING TERRESTRIAL REMOTE SENSING TECHNIQUES

by

Matthieu Sturzenegger
Bachelor of Science (Licence), University of Geneva, 2003
Master of Science (Diplôme), University of Geneva, 2005

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**APPROVAL**

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<tr>
<th>Name:</th>
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</tbody>
</table>

**Examining Committee:**

- **Chair:** Dr. Derek Thorkelson  
  Professor, Department of Earth Sciences

- **Dr. Doug Stead**  
  Senior Supervisor  
  Professor, Department of Earth Sciences

- **Dr. Glyn Williams-Jones**  
  Supervisor  
  Associate Professor, Department of Earth Sciences

- **Dr. Réjean Couture**  
  Supervisor  
  Geological Survey of Canada

- **Dr. William C. Haneberg**  
  Supervisor  
  Haneberg Geoscience

- **Dr. Brent Ward**  
  Internal Examiner  
  Associate Professor, Department of Earth Sciences

- **Dr. Monica Ghirotti**  
  External Examiner  
  Associate Professor, University of Bologna

**Date Defended/Approved:** June 29, 2010
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ABSTRACT

Terrestrial remote sensing techniques including both digital photogrammetry and laser scanning, represent useful complements to conventional field mapping and rock mass discontinuity characterization. Several studies have highlighted practical advantages at close-range (< 300 m), including the ability to map inaccessible rock exposures and hazard reduction related to both traffic and rockfall along investigated outcrops. In addition, several authors have demonstrated their potential to provide adequate quantification of discontinuity parameters. Consequently, their incorporation into rock slope stability investigations and design projects has grown substantially over recent years.

As these techniques are increasingly applied by geologists and geological engineers, it is important that their use be properly evaluated. Furthermore, guidelines to optimize their application are required in a similar manner to standardization of conventional discontinuity mapping techniques. An important thesis objective is to develop recommendations for optimal applications of terrestrial remote sensing techniques for discontinuity characterization, based on a quantitative evaluation of various registration approaches, sampling bias and extended manual mapping of 3D digital models.

It is shown that simple registration networks can provide adequate measurement of discontinuity geometry for engineering purposes. The bias associated with remote sensing mapping is described. The advantages of these techniques over conventional mapping are demonstrated, including reliable discontinuity orientation measurements. Persistence can be precisely quantified instead of approximately estimated, resulting in a new class for extremely persistent discontinuities being suggested. Secondary roughness and curvature can also be considered at larger scales. The techniques are suitable for the definition of discontinuity sets, and the estimation of both trace intensity and block size/shape, if sampling bias is correctly accounted for. A new type of sampling window,
suitable for the incorporation of remote sensing data into discrete fracture network models is presented.

Another significant thesis objective is the extension of terrestrial digital photogrammetric methods to greater distances (> 1 km), using $f = 200$-$400$ mm lenses. This has required a careful investigation of the observation scale effects on discontinuity parameters. The method has been applied in a large open-pit mine and on the Palliser Rockslide. It allows detailed characterization of the failure surfaces, volume estimations and pre-slide topography reconstruction.

**Keywords:** rock mass discontinuity characterization; terrestrial digital photogrammetry; terrestrial laser scanning; sampling bias; observation scale; Palliser Rockslide; Frank Slide; Palabora Open Pit Mine; failure surface; registration
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CHAPTER 1
INTRODUCTION

1.1 Thesis objectives

The stability of rock slopes, both natural and engineered, is highly controlled by discontinuities. Quantification of their characteristics consequently represents a major initial step in stability analyses. Discontinuity mapping commonly involves boreholes, scanlines or sampling windows. Recent developments in terrestrial remote sensing techniques, which include terrestrial digital photogrammetry (TDP) and terrestrial laser scanning (TLS) complement and improve existing rock characterization methods. However, while conventional techniques are standardized and the bias associated with them fully documented, terrestrial remote sensing techniques require further evaluation and constraint in order to optimize their potential and provide accurate measurements. The principal objectives of this research are:

- an evaluation of the benefits of the application of terrestrial remote sensing techniques for rock mass discontinuity characterization on both small rockcuts and large rock slopes,
- the definition of the sampling bias associated with terrestrial remote sensing techniques, including investigation of the observation scale effect on the measurements of discontinuity parameters,
- the extension of close-range terrestrial remote sensing to medium- (>300 m) and long-(>1000 m) range for application on major landslides and large open-pit mines,
- the development of guidelines and recommendations for optimal remote sensing discontinuity characterization, TLS/TDP 3D model registration and incorporation into both discrete fracture network and numerical models. Discontinuity characterization will focus on geometric parameters, including location, orientation, discontinuity sets, persistence, roughness/curvature, frequency, block size and block shape.
1.2 Thesis outline

This chapter presents literature reviews on discontinuity geometric parameters, rock slope stability analysis methods and application of terrestrial digital remote sensing techniques in geosciences and more specifically in engineering geology. The review on discontinuity geometric parameters includes discussion of geological and geometric fracture networks as well as rock mass classification systems, interaction of discontinuities in a rock mass being an essential component of stability analyses.

Chapter 2 provides detailed guidelines for the application of both terrestrial digital photogrammetry and terrestrial laser scanning for rock mass discontinuity characterization. It proposes recommendations on how to plan field surveys in order to optimize the generation of TLS/TDP 3D models. A number of registration approaches are presented, including total station and Differential Global Positioning System (DGPS) surveys. Appendix 1 complements this chapter, providing a step-by-step workflow for both field and office work.

Chapter 3 presents remote sensing methods for discontinuity characterization on rock cuts, at close-range (< 300 m), evaluating the advantages of these technique for quantification of discontinuity location, orientation, persistence and roughness/curvature. A description of potential sampling bias is also provided. This is preceded by an evaluation of a range of approaches for remote sensing 3D model registration, which is intended to aid in optimizing the cost, time and effort spent on a specific field project. This chapter has been published in Engineering Geology.

Chapter 4 discusses the extension of terrestrial remote sensing techniques to medium- (> 300 m) and long-range (> 1000 m). The quality of the generated 3D models is verified and a specific emphasis is placed on the description and quantification of observation scale effects on discontinuity orientation and persistence measurements. An application of the methodology, applied to Turtle Mountain, location of the 1903 Frank Slide, is included. This chapter has been published in Natural Hazards and Earth System Sciences.

Chapter 5 focuses on the characterization and quantification of mean trace length, trace intensity and block size/shape, using terrestrial remote sensing techniques. An
evaluation of existing methods is presented. A new estimation method is outlined and its benefit demonstrated. Data are incorporated into discrete fracture network (DFN) models for the generation of block size and shape distributions. A critical discussion of the limitations in the use of terrestrial remote sensing data for generation of DFN models is provided, based on constraints provided by field-based scanline measurements. This chapter has been submitted to Engineering Geology.

Chapter 6 describes a detailed field and remote sensing-based investigation of the Palliser Rockslide in the Canadian Rocky Mountains. The investigation includes a volumetric analysis of the debris, a reconstruction of the pre-slide topography and discontinuity mapping. A detailed observation of the failure surface morphology has allowed the identification of various types of step-path geometry. This work demonstrates how terrestrial digital photogrammetry can be advantageously incorporated into a landslide investigation project in order to improve our understanding of the failure mechanism through digital mapping and numerical modelling. A modified version of this chapter will be submitted to a journal.

Chapter 7 discusses the main contributions of this research, including an evaluation of the benefits of remote sensing-based discontinuity characterization and the presentation of guidelines for its application. Recommendations for future work are also included.

Appendix 1 complements Chapter 2 by suggesting workflows for both field and post-processing work. The latter includes details about commands used to process data using the Adam Technology and Polyworks software packages. Appendices 2 and 3 present the application of medium- and long-range terrestrial remote sensing techniques in a large open-pit mine (Palabora – South Africa) and on a large landslide (The Frank Slide – Alberta/Canada), respectively. They provide important details on the application of the techniques and potential difficulties. Appendix 2 is published in the 3rd Canada-US Rock Mechanics Symposium (Toronto, May 2009) conference proceedings. Appendix 3 has been written for the Alberta Geological Survey as a technical report. Appendix 4, in table format, summarizes all sites visited during the thesis program and documents a
large remote sensing database available for future research. Finally, Appendix 5 provides a list of all publications by the author during the doctoral research program.

1.3 Literature review

The presence of discontinuities in a rock mass reduces its strength and homogeneity, and plays an important role in rock slope instability. Stability assessments involve the study of the interaction between discontinuities and rock slope morphology through kinematic analysis, limit equilibrium analysis and numerical modelling. These analyses rely heavily on understanding the structural geology of a site and on accurate measurements of discontinuity parameters.

1.3.1 Discontinuity geometric properties

The word “discontinuity” is a general term, which is used for many types of features, including joints, faults, bedding planes and fractures along other directions of weakness (ISRM, 1978; Priest, 1993). In this thesis, if no evidence of movement has been observed, discontinuity will be used to refer to a joint. Three basic physical characteristics of joints in rock are summarized by Pollard and Segall (1987) and illustrated in Fig. 1-1:

- joints have two parallel surfaces that meet at the fracture front,
- these surfaces are approximately planar,
- the relative displacement of originally adjacent points across the joint is small compared to joint length.

Discontinuities appear in outcrops as traces or exposed surfaces, the entire surface being at least partly hidden within rock masses or eroded. Davis and Reynolds (1996) specify that traces and surfaces are planar to curviplanar partial exposures of larger surfaces. This implies that discontinuity length measurements will commonly be subject to sampling bias. Discontinuity measurements may also be affected by orientation bias, depending on the orientation of rock outcrops. In order to minimize this bias and because discontinuity parameters are naturally subject to variability, standardized survey techniques have been developed, which consider discontinuity networks as ensembles (or
sets) and allow application of basic statistical tools to characterize their parameters. In contrast, deterministic characterization considers discontinuities individually.

Figure 1-1. Joint physical characteristics. (a) Idealization of a fracture in a rock mass, b) enlargement of a small region containing the fracture front (Pollard and Aydin, 1988; by permission).

1.3.1.1 Scanline and window mapping techniques

Conventional methods used to systematically sample discontinuity parameters include scanline and window (cell) mapping (Priest, 1993) and must be applied on sub-planar rock faces that are sufficiently large relative to the size and spacing of exposed discontinuities. At least 200 discontinuities should be measured in order to obtain representative samples (Priest, 1993). The principle of scanline mapping is to measure the various parameters of all discontinuities intersecting a straight tape measure. Similarly, for window mapping, the parameters of all discontinuities intersecting or contained within a window are recorded.

Orientation bias occurs when scanlines or windows are not perpendicular to discontinuities. In order to minimize this bias, additional scanlines/windows should be achieved on outcrops with different orientations. Alternatively, a correction factor can be applied on under-represented discontinuity sets, whose normal trends at an acute angle with respect to the normal to the scanline/window (Terzaghi, 1965; Priest, 1993). This geometrical correction \( w \) is applied based on the observed angle between the sampling line/window and the normal to a particular discontinuity set using the following equation:
\[ w = \frac{1}{\cos \delta} \]  

(1-1)

where \( \delta \) is the acute angle between the discontinuity set normal and the sampling line/window (Fig. 1-2a). As the angle \( \delta \) approaches 90°, the cosine approaches zero, and corrected estimates approach infinity, significantly overestimating intensity (Priest, 1993).

Figure 1-2. Sampling bias (after Priest, 1993). (a) Orientation bias correction, (b) censoring (or trimming) of traces, (c) f-bias.

Trace length sampling on planar sampling windows is subject to censoring, truncation, length and f-bias. Truncation occurs because very small traces are difficult to measure. Therefore, trace lengths below some determined cut-off length are not recorded. Truncation is commonly considered as negligible when choosing a small cut-off length compared to the average length (Zhang and Einstein, 1998). Censoring occurs when long discontinuity traces extend beyond the visible exposure, so that one or both ends of the
traces cannot be seen (Zhang and Einstein, 1998). When imposed for sampling purposes, Priest (1993) uses the terms curtailment for censoring and trimming for truncation (Fig. 1-2b). Length bias occurs because longer fracture traces have a greater probability of being sampled than shorter traces and because large fracture surfaces are more likely to appear on an outcrop than smaller ones (Zhang and Einstein, 2000). The f-bias occurs, because the traces representing the intersection between discontinuities and an outcrop are a chord produced by random sections across discontinuity surfaces (Fig. 1-2c) (Priest, 2004), and consequently do not necessarily represent the diameter of circular discontinuities. Other sampling artefacts include pattern heterogeneity, which refers to a change in fracture parameters with a change in position. Rohrbaugh et al. (2002) describe a range of possible geometries subject to pattern heterogeneity. Corrections for this bias are summarized in Zhang and Einstein (2000).

1.3.1.2 Discontinuity position

Position consists of the ground coordinates and elevation, relative or absolute, of the discontinuity center. In practice, due to sampling bias, only the position of the apparent discontinuity center may be measured.

1.3.1.3 Discontinuity orientation and discontinuity sets

The orientation of a discontinuity is usually quantified by the dip of the line of steepest declination and the dip direction, measured clockwise from the true north. When discontinuities are grouped into sets, it is common to use spherical (hemispherical) distributions, such as the Fisher distribution (Priest, 1993). The Fisher distribution describes a symmetrical distribution of orientation about a mean. An indication of the degree of clustering is provided by the Fisher dispersion coefficient ($K$) a large value indicating a tight cluster. The probability density function is:

$$f(\theta) = \frac{K \sin \theta e^{K \cos \theta}}{e^K - e^{-K}}$$ (1-2)

where $\theta$ is a discontinuity orientation value.
Discontinuity orientation is commonly used to delineate structural domains (Piteau, 1973). A domain comprises a volume of rock mass with constant characteristics, such as a constant orientation of dominant discontinuity sets, constant rock mass strength properties and homogeneous rock type (Martin and Tannant, 2004). These authors developed a technique, which compares orientation data of different regions, and in which the discontinuity orientations of two regions are analyzed, using a correlation coefficient.

1.3.1.4 Discontinuity shape and termination

Although little is known about joint shape in massive rocks, rib marks suggest that an elliptical geometry may be common (Pollard and Aydin, 1988). In contrast, joints produced by cooling of a lava flow or joints within layered sedimentary rocks are roughly rectangular. For mathematical convenience, discontinuities are commonly assumed to be thin planar circular discs. Zhang et al. (2002) and Zhang and Einstein (2010) questioned this assumption and proposed a model with planar elliptical or rectangular discontinuities, depending on whether their area is restricted or unrestricted. With this model, they obtain a log-normal distribution of trace lengths and remark that the orientation of the sampling plane has an effect on trace length, which is not the case if discontinuities are assumed to be circular.

Discontinuity termination can occur within the intact rock or against another discontinuity. The nature of the termination has a major influence on discontinuity shape and persistence. The termination index is the ratio between the number of discontinuities whose semi-trace terminations are in intact rock and the total number of discontinuities. It provides an idea of the amount of rock bridges in a rock mass (Priest, 1993). When discontinuities interact with each other, three main types of termination/intersection can be recognized (Davis and Reynolds, 1996):

- Y-intersection (e.g., columnar basalt),
- X-intersection (e.g., conjugate fractures),
- T-intersection (younger fracture terminates against an older one).
1.3.1.5 Discontinuity roughness

Roughness is the deviation of a discontinuity surface from perfect planarity and can be described at various observation scales. Curvature, defined by Priest (1993) as surface irregularities with a wavelength greater than 100 mm, includes the ISRM (1978) primary roughness, or waviness. Secondary roughness, or unevenness, considers the scale of surface asperities and can be qualified as rough, smooth or slickensided.

Roughness is commonly quantified using the joint roughness coefficient (JRC), an important parameter influencing discontinuity shear strength and dilation. Barton and Choubey (1977) incorporate the JRC into the discontinuity shear strength equation:

\[
\tau = \sigma'_n \tan \left[ \text{JRC} \log_{10} \left( \frac{\text{JCS}}{\sigma_n} \right) + \phi_b \right]
\]  

(1-3)

where \( \sigma'_n \) is the effective normal stress, JCS the wall compressive strength and \( \phi_b \) the basic friction angle.

The JRC can be estimated by creating a simplified discontinuity surface profile (ISRM, 1978) and comparing it with standard profiles, published by Barton (1973) and Barton and Choubey (1977) (Figs. 1-3 and 1-4). Maerz et al. (1990) and Tse and Cruden (1979) propose more objective JRC quantification methods, based on the ratio between true discontinuity surface profile length and projected length along a best-fit plane. Lee et al. (1990) use the joint fractal dimension, assuming that roughness is scale-dependant.
Figure 1-3. Standard profiles defining joint roughness coefficient JRC (Barton, 1973; by permission).
Figure 1-4. Roughness profiles and corresponding JRC values (Barton and Choubey, 1977; by permission).
In the Rock Mass index (RMi) (Palmström, 1996), both waviness and unevenness are rated and incorporated in a joint condition factor, which also includes factors for joint length and continuity, and joint surface alteration. Recent work by Fardin et al. (2004), Haneberg (2007) and Oppikofer (2009) has shown that discontinuity surface profiles of the secondary roughness can be easily obtained from laser scanning or digital photogrammetry 3D models. Primary roughness measurement requires higher resolution models.

1.3.1.6 Discontinuity aperture

Aperture is the distance between adjacent walls of a discontinuity, in which the intervening space is air, water or infill. It can result from shear displacement of discontinuities having appreciable roughness, from tensile opening, from outwash and from solution (ISRM, 1978). It is measured with a ruler graduated in millimetres or with a feeler gauge. Ortega et al. (2006) proposes a very fine fracture-aperture comparator. Steep discontinuities that have opened in tension as a result of valley erosion or glacial retreat may have very large apertures.

Aperture controls fracture porosity, which in 3D is defined as the volume of fractures per unit volume of rock mass. In 1D and 2D, aperture represents the summed apparent apertures of fractures crossed per unit length of sampling line and the cross-sectional area of fracture traces per unit area of sampling surface, respectively (see Table 1-1).

1.3.1.7 Discontinuity persistence

Persistence is the extent of a discontinuity plane and is usually measured as the one-dimensional length of a trace exposed on a rock surface (ISRM, 1978). When possible, the trace length should be measured in both dip and strike directions. It is often assumed that trace lengths follow a negative exponential distribution, however, the exact distribution is extremely difficult to estimate, because, in a window, a number of trace measurements are biased. Other distributions, including log-normal and power-law, are proposed (Ortega and Marrett, 2000; Zhang and Einstein, 2000; Priest, 2004).
When persistence is estimated along scanlines, Priest (1993) recommends measuring semi-traces, i.e., the portion of trace lengths lying on one side of the scanline. This sampling method allows the application of statistical techniques to estimate true trace length distributions (Priest, 1993 and 2004). However, Villaescusa and Brown (1992) show that semi-trace lengths may have a different distribution form than full trace lengths.

Measurements of mean trace length are also commonly accomplished using sampling windows (Fig. 1-5). Methods suggested by Pahl (1981) and Kulatilake and Wu (1984a), using rectangular sampling windows, are applicable to a discontinuity set with a single orientation value and an orientation described by a probabilistic distribution, respectively. They consider both length bias and censoring.

Mauldon (1998), Zhang and Einstein (1998) propose a method to estimate the true trace length distribution (mean and standard deviation) using a circular window of finite size. The true (unbiased) trace length distribution differs from the measured distribution, which considers only a sample (window) of the entire trace population. This method is applicable to traces with arbitrary orientation distributions and can be used to estimate the mean trace length of more than one set of discontinuities. As for other trace length distribution-free end-point estimators, length bias and censoring are avoided. The method uses the numbers of traces \( N \) intersecting the window, the number of traces \( N_0 \) with

![Figure 1-5. Discontinuities sampled on a rectangular window (after Pahl, 1981).](image-url)
both ends censored (transecting), and the number of traces \((N_2)\) with both ends observed (contained) (Fig. 1-5). The true mean trace length \((\mu_i)\) and true standard deviation \((\sigma_i)\) are expressed as:

\[
\mu_i = \frac{\pi(N + N_0 - N_2)}{2(N - N_0 + N_2)} c
\]

\[
\sigma_i = \mu_i (COV_i)_m
\]

(1-4)

(1-5)

where \(c\) is the radius of the circular window and \((COV_i)_m\) is the coefficient of variation of the measured trace lengths, i.e., the ratio of the measured standard deviation to the measured mean. Measured and true COV are assumed to be the same. Similarly, it is assumed that the measured and true trace length distributions have the same form. Zhang and Einstein (2000) implement the above calculated true trace length distribution in an equation by Warburton (1980), which considers a stereological relationship between chords (traces measured on sampling windows) and associated diameters for specific discontinuity sets, discontinuity shape being assumed circular. Problems involving elliptical discontinuities have been solved by Zhang et al. (2002).

Mauldon et al. (2001) further developed a method, using a circular scanline and a circular window, to estimate trace parameters. This method is based on the number \((m)\) of joint endpoints inside a circular window and the number \((n)\) of joint intersections with a circular scanline (Fig. 1-6). This method allows quantification of true mean trace length \((\mu)\) and is also used to estimate trace density \((\rho)\) and trace intensity \((I)\) (see section 1.3.1.8):

\[
\mu = \frac{\pi r \left( \frac{n}{m} \right)}{2}
\]

(1-6)

\[
\rho = \frac{m}{2\pi r^2}
\]

(1-7)

\[
I = \frac{n}{4r}
\]

(1-8)

where \(r\) is the radius of the circular window.
Using the above mentioned techniques, is it important that the size of any circular window be defined so that \( N_0 \neq N \) (all joints are not censored at both ends) and \( N_2 \neq N \) (all joints are not contained within the window) (Zhang and Einstein, 1998). When applying the method of Mauldon and co-workers, the selected windows should be larger than the mean block size and a minimum of 30 “\( m \)” counts are recommended to reduce the variability of estimates (Rohrbaugh et al., 2002). In addition, it is suggested that multiple windows of the same size and at different locations be used.

Song (2006) noted that a sufficient number of traces sometimes cannot be sampled on a single planar sampling window and suggested a method to estimate areal density and mean trace length on non-planar surfaces. In contrast to the apparent areal frequency estimator mentioned previously, the proposed method includes an orientation variable, representing the angle between the sampling window and the discontinuity set orientation. Consequently, this method is only applicable to a randomly located parallel disc model, although a variation of discontinuity orientation within the set can be tolerated up to a Fisher K value of 5.

1.3.1.8 Discontinuity frequency

Discontinuity frequency can be expressed by a variety of parameters, including density, intensity and spacing. Dershowitz and Herda (1992) developed a unified system of discontinuity frequency measures. This system defines fracture frequency in terms of
the dimensions of the sampling regions (e.g. scanline, trace map, volume) and the dimensions of the features (e.g. count, trace, surface). The specific terminology used within the framework of the Discrete Fracture Network (DFN) code FracMan (Dershowitz et al., 1998; Golder Associates, 2009) is as follows. Fracture density is defined as the number of fractures per unit volume of rock mass ($P_{30}$), the number of traces per unit area of a sampling plane ($P_{20}$) or the number of fractures per unit length of scanline or borehole ($P_{10}$). Fracture intensity is defined as the area of fractures per unit volume of rock mass ($P_{32}$) or the length of fracture traces per unit area of sampling surface ($P_{21}$) or as the linear intensity ($P_{10}$).

**Table 1-1.** Graphical illustration of FracMan fracture quantification parameters. Green, yellow and orange shading indicate intensity, density and porosity dimensions, respectively (based on Slide No. 20 from http://fracman.golder.com/Gallery/guidtour.asp).

<table>
<thead>
<tr>
<th>Dimension of feature</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension of sampling region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>$P_{00}$ Length$^0$ Number of fractures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$P_{10}$ Length$^{-1}$ Number of fractures per unit length of scanline (Frequency or linear intensity)</td>
<td>$P_{11}$ Length$^0$ Length of fractures intersects per unit length of scanline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$P_{20}$ Length$^{-2}$ Number of traces centres per unit area of sampling plane (Areal density)</td>
<td>$P_{21}$ Length$^1$ Length of fracture traces per unit area of sampling plane (Areal intensity)</td>
<td>$P_{22}$ Length$^0$ Area of fractures per unit area of sampling plane</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$P_{30}$ Length$^{-3}$ Number of fracture centres per unit volume of rock mass (Volumetric density)</td>
<td>$P_{32}$ Length$^{-1}$ Area of fractures per unit volume of rock mass (Volumetric intensity)</td>
<td>$P_{33}$ Length$^2$ Volume of fractures per unit volume of rock mass</td>
<td></td>
</tr>
</tbody>
</table>

Linear frequency is the number of fractures per unit length. It can be measured separately for individual discontinuity sets or for the entire discontinuity population.
When considering individual sets, measurement of linear frequency must be corrected with equation 1-1. When considering the entire population, linear frequency varies according to the sampling direction. Hudson and Priest (1983) provided equations to calculate the direction of maximum frequency (trend, $\alpha_m$ and plunge, $\beta_m$):

$$
\alpha_m = \tan^{-1}\left(\frac{a}{b}\right) \\
\beta_m = \tan^{-1}\left(\frac{c}{\sqrt{a^2 + b^2}}\right)
$$

(1-9)

The frequency along that direction is:

$$
\lambda_{s_{\text{max}}} = \sqrt{a^2 + b^2 + c^2}
$$

(1-10)

where $a$, $b$ and $c$ are the x, y and z components of the $\lambda_{s_{\text{max}}}$ vector, respectively (Hudson and Priest, 1983).

The linear frequency is the reciprocal of spacing. The mean spacing is the mean distance between adjacent discontinuity intersections along a scanline. For individual sets, the apparent spacing along that scanline is related to the true spacing using the following equation:

$$
S_{\text{app}} = S \cos \delta
$$

(1-11)

where $S$ and $S_{\text{app}}$ are the true and apparent spacing, respectively, and $\delta$ is the angle between the sampling line and the normal to a discontinuity set.

Priest and Hudson (1976) have shown that the superimposition of non-random individual sets, as a result of different geological events, gives rise to a random occurrence process when the sets are aggregated. The random occurrence of discontinuities along a line is an example of a one-dimensional Poisson process. The associated spacing values follow a negative exponential distribution.

As a result of the observation scale effect, Ortega et al. (2006) state that fracture density and intensity are only meaningful if the fracture detection threshold is quantified and propose the use of cumulative-frequency fracture-size distributions, which have the advantage of facilitating a comparison between scanline data collected at various scales by providing a scale-independent estimation of fracture abundance. Results have to be
normalized to a common range of fractures, so that datasets collected at various scales of observation can be compared. Ortega et al. (2006), Ortega and Marrett (2000) and Marrett et al. (1999) report that log-log plots of cumulative frequency versus trace length show power law distributions, suggesting that trace length data at the studied observation scales could be used to predict trace length at other observation scales (Fig. 1-7).

Figure 1-7. Cumulative-frequency fracture-size distribution. Fracture size is directly related to aperture measurements. Fracture abundance can be characterized both as intensity (cumulative frequency) or average spacing (inverse of cumulative frequency) (Ortega et al., 2006; by permission).

Areal frequency can be estimated using sampling windows. Kulatilake and Wu (1984b) developed a method to estimate trace density, based on the probability that the midpoint of a given trace lies inside a window. The drawback to this method is that it is trace length distribution-dependent, and the underlying distribution of trace length is generally unknown. The method by Mauldon et al. (2001) presented in Section 1.3.1.7, can also be used to estimate trace density and intensity using a circular scanline and a circular window in combination with Eqs. 1-7 and 1-8, respectively. Finally, areal density
and intensity can simply be calculated as the number of discontinuity centers per area and the sum of discontinuity trace lengths per area, respectively.

The most fundamental measure of discontinuity frequency is the volumetric frequency \( P_{32} \), but its measurement is impractical. Consequently, it is current practice to measure discontinuity areal \( P_{21} \) or linear \( P_{10} \) frequency and then assess \( P_{32} \) on the basis of a linear correlation (Dershowitz et al., 2000):

\[
P_{32} = C_{31} P_{10} \tag{1-12}
\]

\[
P_{32} = C_{32} P_{21} \tag{1-13}
\]

where \( C_{31} \) and \( C_{32} \) are constants of proportionality depending on fracture orientation, radius size distribution and the orientation of the sampling window or scanline.

Other methods for the quantification of discontinuity frequency include the volumetric joint count, \( J_v \) (Palmström, 1982) and the Rock Quality Designation (RQD) (Deere, 1963). The RQD represents the percentage of the sampling line consisting of spacing values (or intact rock pieces) equal or greater than a certain value (usually 0.1 metre). The volumetric joint count is expressed as:

\[
J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots + \frac{1}{S_n} + \frac{Nr}{5} \tag{1-14}
\]

where \( 1/S_n \) are the joint frequencies of \( n \) sets and \( Nr/5 \) is a parameter accounting for \( Nr \) random joints.

1.3.1.9 Block size and shape

Block dimensions are determined by discontinuity spacing, orientation, the number of sets and the persistence of the discontinuities delineating potential blocks. Block size is an important parameter of some rock mass classification systems. The mean block volume, \( V_0 \), can be calculated using the following equation (Palmström, 1996; Cai et al., 2004):

\[
V_0 = \frac{S_1 S_2 S_3}{\sin \gamma_1 \sin \gamma_2 \sin \gamma_3} \tag{1-15}
\]
where $S_1$, $S_2$, $S_3$ are the spacing of joint sets 1, 2 and 3, and $\gamma_1$, $\gamma_2$, $\gamma_3$ the acute angles between the joint sets.

This equation is usable for three sets of persistent joints. When irregular jointing is encountered, because it is difficult to delineate sets, Cai et al. (2004) suggest measuring the dimensions of representative blocks in the field. An alternative is to use indirect measurements using RQD, volumetric joint count or weighted joint density. Methods and correlations to determine the block volume are detailed by Palmström (1996 and 2005).

When joints are non-persistent, an equivalent block volume can be estimated by adding a joint persistence factor to Eq. 1-15:

$$V_b = \frac{S_1 S_2 S_3}{\sin \gamma_1 \sin \gamma_2 \sin \gamma_3 \sqrt{p_1 p_2 p_3}}$$

(1-16)

where $p_i$ is the joint persistence factor. If $\overline{l_i}$ is the accumulated joint length of set $i$ in the sampling plane and $L$ the characteristic length of the rock mass under consideration,

$$p_i = \frac{\overline{l_i}}{L} \quad l_i < L$$

$$p_i = 1 \quad l_i \geq L$$

(1-17)

Cai et al. (2004) estimated that, if the joint length is only about 20% of the characteristic length of the rock mass under consideration, the equivalent block volume is about five times larger than that with persistent joints. Figure 1-8 illustrates the effect of non-persistent joints in the creation of blocks (block area in the 2D example). This is due to the presence of rock bridges, which are defined as small bridges of rock separating coplanar or non-coplanar discontinuities.
Figure 1-8. Effect of non-persistent joints in the creation of blocks (block area in 2D). (a) Joint pattern with 2 sets of discontinuity, (b) actual blocks created after deletion of joints terminating inside blocks (Kim et al., 2007; by permission).

Block shape is commonly described as a ratio between the edge lengths of an orthogonal block. For example, the shape factor ($\beta$) is estimated using the following equation (Palmström, 1996):

$$\beta = 20 + 7a3/a1$$  \hspace{1cm} (1-18)

where $a3$ and $a1$ are the longest and shortest dimension of a block, respectively.

Kalenchuk et al. (2006) propose the Block Shape Characterization Method (BSCM), whose parameters $\alpha$ and $\beta$ characterize the flatness and the elongation of a block, respectively. This classification is shown on Fig. 1-9a. In addition, when combining the block shape distribution with block size distribution of a rock mass, the BSCM can differentiate the shape of small or large blocks (Fig. 1-9b, 1-9c and 1-9d).

In Eqs. 1-15 and 1-16, the main parameters used to calculate block size are related to mean spacing and mean orientation of discontinuity sets. Sturzenegger et al. (2007d) also propose a technique to visualize mean block size and shape in 3D. In reality, spacing and orientation have a natural variability and consequently, they are better described by distributions. Discrete fracture network (DFN) models allow derivation of block size and
shape distribution, based on discontinuity orientation distribution, trace length
distribution and frequency measurements. DFN models will be presented in Section
1.3.3.

Figure 1-9. (a) Block shape diagram to classify blocks according to the shape parameters α and β,
(b) block volume distribution as a function of a threshold size, (c) and (d) illustration of
a simulated rock mass dominated by elongated bar-shaped rock blocks. The upper
portion of the block shape diagram (d) is densely clustered. The histogram of block
shape distribution (c) within each block volume bin indicates that smaller blocks occur
in all shape types, while larger blocks are completely dominated by elongated shapes
(Kalenchuk et al., 2006; by permission).
1.3.2 Joint patterns and geologic models

The interaction between several discontinuity sets can result in a number of various joint patterns (Fig. 1-10), which will differ according to several parameters including joint continuity, discontinuity set orientation and the type of intersection. In some cases, joint patterns are associated with specific geologic and structural processes, and can be described by typical geologic models.

Figure 1-10. Schematic illustration of major multiple joint patterns (Pollard and Aydin, 1988; by permission). (a) Two orthogonal and continuous joint sets (+ intersections), (b) two non-orthogonal and continuous joint sets (X intersections), (c) two orthogonal, one continuous and one discontinuous (T intersections), (d) two non-orthogonal joint sets, one continuous and one discontinuous, (e) two orthogonal and discontinuous joint sets, (f) two non-orthogonal, discontinuous joint sets, (g) triple intersections with discontinuous joints at various angles, (h) triple intersections with discontinuous joints at 120° angles.

1.3.2.1 Layered sedimentary rock masses

Joint networks in layered sedimentary rock masses are commonly composed of one set of fractures along the bedding and two orthogonal joint sets normal to it (Fig. 1-10c) (Josnin et al, 2002; Doolin and Mauldon, 2001). The persistence of orthogonal joints is limited vertically by bedding planes, and horizontally by older pre-existing joints (Josnin et al., 2002). As a result, joint shape is typically rectangular with a mean height/length ratio equal to 0.5 (Josnin et al., 2002).
Odling et al. (1999) differentiate orthogonal joint sets in stratabound systems from those in non-stratabound systems. Stratabound systems are characterized by regularly spaced orthogonal joints with log-normal length distribution. They have a high connectivity and fracture intensity increases (i.e., fracture spacing decreases) with decreasing bed thickness (Ortega et al., 2006). In non-stratabound systems in massive rock types, where the influence of bedding is less marked, joints orthogonal to bedding are irregularly spaced and form clusters, their length following power-law distributions.

1.3.2.2 Igneous plutons

In igneous plutons, fractures (veins, joints and dikes) are related to the rock fabric through their relative orientations (Pollard and Aydin, 1988). Cloos (1922) proposed a model, which includes steeply dipping tensile joints perpendicular (cross joints) or parallel (longitudinal joints) to flow lines (Fig. 1-11). Steep joints, which strike at angles of about 45° to the flow lines (diagonal stretching joints) are interpreted as shear fractures.

Figure 1-11. Block diagram showing ideal primary fracture pattern in a granitic pluton (Cloos, 1922; by permission).
1.3.2.3 Columnar joints

Columnar joints are networks of interconnected tension fractures that divide solids (mostly volcanic bodies) into prisms, or columns, with locally parallel axes and polygonal cross sections (Degraff and Aydin, 1987). They consist of mode-I cracks that form under the influence of thermally induced tensile stress. This model of jointing is quite systematic at the base of cooled lava flows, while the upper part is at least partly characterized by irregular joint patterns. Degraff and Aydin (1987) showed that each joint surface is actually the result of a large number of distinct joint increments. The shape of such joint surfaces is rectangular, typically with a large height/length ratio. When columnar-jointed volcanics outcrop and are subject to gravity, they commonly fail by block toppling, the prismatic blocks being delimited by a set of widely spaced, non-persistent joints orthogonal to the columns axis (Wyllie and Mah, 2004).

1.3.2.4 Folds

Different types of discontinuities are created in response to flexural-slip folding mechanisms. On the outer arc of a folded layer, layer-parallel stretching can be accommodated by the formation of tension fractures perpendicular to the direction of layer-parallel stretching (Fig. 1-12a). Conjugate normal-slip faults can also form in such a way that their line of intersection is parallel to the axis of folding. On the inner arc, thrust-slip faults and/or cleavage accommodate layer-parallel shortening (Fig. 1-12a). Conjugate thrust-slip faults intersect in a line parallel to the axis of folding, and the cleavage is typically aligned parallel to the axial surface of the major fold.

Three classes of fold-related joints can be distinguished: cross joints, longitudinal joints, and oblique joints (Fig. 1-12b). Cross joints are mode I joints that are ideally aligned perpendicular to the axis of folding. They are planar, regularly spaced and often vein filled. Longitudinal joints are mode I joints oriented subparallel to the axial surfaces of folds. They tend to be through-going, planar, continuous structures. Finally, oblique joints ideally comprise two conjugate sets of shear joints (mode II and III). They are arranged such that the axial surface of the fold bisects the obtuse angle of intersection of the joint sets.
**1.3.3 Discrete fracture network models**

The discrete fracture network (DFN) approach allows generation of realistic fracture network models, which can account for the stochastic character of discontinuity properties, the influence of geological structures such as folds and faults, and the interdependence of fractures (Josnin et al., 2002). The stochastic nature of the DFN model generation process is such that there are an infinite number of possible realisations of the 3D discontinuity system based on the mapped data. The mapping process is itself random due to the nature of how fractures are presented in available windows. With the exception of fully explicit modelling of an individual fracture or simplified fracture set, the stochastic approach provides the best option for creating realistic geometric models of fracturing. In particular, they avoid the use of simplistic fracture networks assuming ubiquitous, infinite length fractures and fracture sets with constant orientation (Rogers et al., 2006).

The required parameters for the generation of DFN models are discontinuity orientation distribution, trace length distribution and fracture intensity. Discontinuities can be generated according to various spatial geometric or geologic models. Several fracture geometric models are presented by Dershowitz and Einstein (1988) and Staub et
The Baecher Disk Model generates a fracture network from fracture centres that are distributed uniformly in space. Dershowitz (1979) extended it (Enhanced Baecher Model) by providing for polygonal fracture shapes and fracture terminations (Fig. 1-13a); if fractures intersect, a termination probability will determinate whether to truncate the fracture at the intersection. The Levy-Lee Fractal Model generates clusters of smaller fractures around widely scattered, larger ones (Fig. 1-13b). In the Nearest Neighbour Model, fracture intensity ($P_{32}$) decreases exponentially with distance from “major features” (Fig. 1-13c).

Figure 1-13. Fracture geometric models (Elmo, 2006; by permission). (a) Enhanced Baecher Model, (b) Levy-Lee Fractal Model, (c) Nearest Neighbour Model.
1.3.4 Rock mass classification systems

Rock mass strength and deformability are controlled partly by the intact rock properties, and partly by discontinuity geometric and mechanical properties. Rock mass classification systems represent convenient tools to combine both intact rock and discontinuity properties.

The generalized Hoek-Brown empirical failure criterion is an example of a tool for estimating rock mass strength (Hoek et al., 2002):

\[ \sigma'_1 = \sigma'_3 + \sigma_{ci} \left( m_b \frac{\sigma'_3}{\sigma_{ci}} + s \right)^a \]  

(1-19)

where \( \sigma'_1 \) and \( \sigma'_3 \) are the maximum and minimum effective stresses, \( \sigma_{ci} \) the intact rock uniaxial compressive strength, \( m_b \) the value of the Hoek-Brown constant \( m_i \) for a rock mass, \( s \) and \( a \) constants.

Parameters \( m_b \), \( s \) and \( a \) are rock material constants modified using the Geological Strength Index (GSI), which is used as a system to estimate the reduction in rock mass strength for different geological conditions, through observation of interlocking of rock pieces and discontinuity surface quality (Fig. 1-14). The advantage of the GSI approach is that it relates rock mass strength directly to geological observation. Hoek and Brown (1997) state that GSI must be applied to slope stability only when the potential for structurally controlled failures has been eliminated, i.e., when the rock mass can be considered as an isotropic material. In addition, a disturbance factor (D) should be used to compensate for blasting damage (Hoek and Diederichs, 2006).

The estimation of the GSI is to some extent subjective and should be presented as a range. Cai et al. (2004) developed a quantitative approach to assist in the use of the GSI system, using the block volume and a joint condition factor as quantitative characterization factors. Block volume is estimated based on joint set orientation, spacing and persistence (Eqs. 1-15 to 1-17), and the joint condition factor using rating systems accounting for joint waviness, joint smoothness and joint alteration. Figure 1-15 shows the chart for GSI adapted for these quantitative characterization factors.
GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced is water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

<table>
<thead>
<tr>
<th>SURFACE CONDITIONS</th>
<th>DECREASING SURFACE QUALITY</th>
<th>DECREASING INTERLOCKING OF ROCK PIECES</th>
<th>N/A</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities</td>
<td></td>
<td></td>
<td>90</td>
<td>80</td>
</tr>
<tr>
<td>BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets</td>
<td></td>
<td></td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>VERY BLOCKY - interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets</td>
<td></td>
<td></td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity</td>
<td></td>
<td></td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces</td>
<td></td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes</td>
<td></td>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 1-14. Chart for GIS estimates from geological observations (Marinos et al., 2005; by permission).
Figure 1-15. Quantification of the GSI chart (Cai et al., 2004; by permission).
Brown (2008) highlights the limitations of the generalized Hoek-Brown failure criterion in rocks with low strength (UCS < 15 MPa) and low GSI, where strength is mostly controlled by soil-like intact rock. Furthermore, Carter et al. (2008) states that, under high stress and low confinement conditions, the generalized Hoek-Brown failure criterion overestimates the strength of hard rock masses with GSI larger than 65 and rock constant (m) superior to 15, because tensile brittle failure is more likely to occur (Fig. 1-15). This observation has been further demonstrated by Alzo’ubi (2009) who studied the role of tensile strength in fracture initiation under low confinement stress conditions in rock slopes, for complex failure mechanisms such as buckling and flexural toppling (Fig. 1-16).

Figure 1-16. Buckling (a) and flexural toppling (b) associated with tensile failure in rock slopes (Alzo’ubi, 2009; by permission).

Other rock mass classification systems include Palmström’s Rock Mass Index (RMi), which accounts for block size, joint roughness, alteration, size and termination (Palmström, 1996). The Slope Mass Rating (SMR) (Romana, 1985) is an adaptation for rock slopes of Bieniawski’s Rock Mass Rating (RMR) (Bieniawski, 1989). In addition to RMR’s parameters, strength of intact rock, RQD, spacing of discontinuities, condition of discontinuities and water inflow through discontinuities, the SMR introduces factors related to fracture geometry. These factors include parallelism between joints and slope face strike, joint dip angle in the planar mode of failure, relationship between the slope
face and joint dip and an adjustment factor for the method of excavation (Romana, 1993). The classification must be applied for each joint system and the minor score of SMR is retained for the overall slope.

Monte (2004) presented the Digital Rock Mass Rating (DRMR) using basic image processing and calculations to estimate a classification rating from digital images of rock masses. The system incorporates fracture information from a discontinuity trace map, including number of sets, trace length, trace spacing, large-scale roughness, block volume, rock bridge percent and image texture.

1.3.5 Rock slope stability analysis

The stability of competent rock masses is often controlled by a few persistent discontinuities. Three basic failure mechanisms in rock slopes are planar sliding, wedge sliding and toppling (Wyllie and Mah, 2004). Planar sliding (Fig. 1-17a) occurs if a plane of weakness daylights into free space. In dry conditions, the plane inclination must be greater than its friction angle. To enable sliding, lateral and/or rear release surfaces must exist. Wedge sliding (Fig. 1-17b) occurs if the line of intersection of two discontinuities daylights. The plunge of the line of intersection must be steeper than the average friction angle of the two discontinuities. Note that depending on the geometry of a wedge, the failure mechanism could be planar sliding along only one of the two discontinuities, the other one acting as a lateral release surface. Such a mechanism can be assessed using the Hocking’s test (Hoek and Bray, 1981).
Figure 1-17. Basic failure mechanisms (Hoek and Bray, 1981; by permission). (a) Planar sliding, (b) wedge sliding.

The feasibility of these failure mechanisms can be estimated geometrically with kinematic analysis. Conventional limit equilibrium analysis for planar and wedge sliding uses force vectors to estimate a Factor of Safety (FoS), which is the ratio between resisting force and driving force. The software RocPlane and Swedge (Rocscience Inc., 2009) are commonly used for planar failure sliding and wedge failure, respectively. The detailed equations for calculating FoS can be found in Wyllie and Mah (2004).

There are two main types of toppling failure. Block toppling (Fig. 1-18a) occurs typically in bedded sandstones and columnar-jointed volcanics, where individual columns are formed by a set of discontinuities dipping steeply into the face, and a second set of widely spaced orthogonal joints defining the column height. The short columns forming the toe of the slope are pushed forward by the loads from the longer overturning columns behind, and this sliding of the toe allows further toppling to develop higher up the slope. As a result, the block toppling failure mechanism involves a combination of sliding along the base of the short blocks and toppling around the center of gravity of longer blocks (Fig. 1-19a). The initiation of the toppling component requires interlayer slip (Fig. 1-19b); consequently, a condition for toppling to occur is that the direction of applied compression makes an angle greater than the friction angle with respect to the normal to the layers. Bedding must be subparallel (± 30°) to the slope.
Flexural toppling (Fig. 1-18b) occurs mostly in thin-bedded sedimentary rocks, where breaking at the base of continuous columns of rock happens by flexure, instead of along a pre-existing discontinuity set for block toppling. Interlayer slip is required. This complex failure mechanism can be studied using distinct element methods, as shown previously in Fig. 1-16b, limit equilibrium analysis being inappropriate.

Conventional limit equilibrium analyses assume that failure surfaces follow through-going discontinuities. On small slopes, such as roadcuts or mine benches, individual joints can be persistent enough to define discrete sliding or toppling blocks. In
contrast, on large slopes, such as high mountain rock slopes or large open-pit mine walls, failure surfaces need to follow a combination of pre-existing discontinuities and intact rock fractures in order to be through-going. Intact rock fractures occur through rock bridges. Figure 1-20 illustrates different possible failure paths composed of one or two discontinuous joint sets and rock bridges. Jennings (1970) proposed limit equilibrium analyses with discontinuous coplanar and non-coplanar joint sets. The approach used by Einstein et al. (1983) and Moffit et al. (2007) consists of determining the “critical path” representing the combination of pre-existing discontinuities and intact rock fractures, which has the lowest factor of safety or contains the lowest percentage of intact rock bridges. Other programs allowing step-path analysis failures include Bstepp (Miller et al., 2007) and STEPSIM (Baczynski, 2008).
Another common approach to account for intact rock bridges along failure surfaces in limit equilibrium analyses is to imply their presence using an apparent cohesion and tensile strength (Jennings, 1970; Eberhardt et al., 2004; Karami et al., 2007). This can also be done using distinct element numerical methods, such as the codes UDEC and 3DEC (Fig. 1-21a) (Itasca, 2009a and 2009b), which allow finite displacement of discrete blocks along digitized discontinuities and the incorporation of stress fields. Distinct element methods are usually preferred to finite element methods to model fractured rock masses, precisely because actual movement along discontinuities can be simulated, although the effect of existing discontinuities in terms of stress distributions and the yielding of intact rock can also be represented in finite elements methods.
Explicit representation of the intact rock bridge fracturing can be achieved using more advanced numerical codes. Alzo‘ubi (2009) and Wang et al. (2003) use the Voronoi tessellation option in UDEC (Fig. 1-21b) and the particle flow code (PFC), respectively, to study the development of rock slope failure where breakage of intact rock bridges is involved. These techniques mimic fracturing along grain boundaries or larger flaws in rock (Alzo‘ubi, 2009). Stead et al. (2006) and Elmo et al. (2009) present another method using the hybrid finite-/discrete elements ELFEN code, which allows for the generation of new fractures within intact rock, through adaptive remeshing techniques coupled with contact search algorithms. Finally, Cundall and Damjanac (2009) describe the Slope Model code capable of simulating intact rock breakage in 3D jointed rock slopes using lattices connected by springs.

1.3.6 The use of terrestrial remote sensing techniques in geoscience

2D photoanalysis has been used by many authors as a trace mapping tool. It is particularly useful for the quantification of trace length, spacing, fracture intensity and block size (Tsoutrelis et al., 1990). Indeed, photographs can cover inaccessible areas, providing comprehensive samples of a rock cut. Some authors (e.g., Franklin et al., 1988; Reid and Harrison, 2000; Lemy and Hadjigeorgiou, 2003) attempted to automate the trace mapping process. On 2D photographs, orientation measurements can be obtained
only in specific cases, when measurements on two or more different outcrop face orientations can be combined (Franklin et al., 1988; Kemeny and Post, 2003) or if regular fracture network models can be assumed (Crosta, 1997).

Analytical photogrammetry has been used as a tool to provide 3D measurements of discontinuities. Early work used phototheodolites to survey 3D points along specific discontinuities to measure their orientation (Wickens and Barton, 1971; Allam, 1978). Other parameters such as discontinuity position, size, spacing and roughness could also be estimated. Discontinuity characteristics obtained in this way were found to agree well with values obtained using standard manual procedures. Although photogrammetric methods such as this can provide only limited information on discontinuity orientation, they are potentially valuable for measuring discontinuity surface geometry both at small and large scale.

The use of analytical photogrammetry in rock cut analysis was limited in the past, however, recent developments in computer performance and increased use of digital photographs have stimulated advances in photogrammetric software allowing rapid construction of 3D models. Consequently, terrestrial digital photogrammetry has become available to non-photogrammetrists and is finding widespread application in geotechnical engineering. For further details concerning the theory of analytical photogrammetry, the reader should refer to Slama (1980) and Atkinson (1996).

Unlike analytical photogrammetry, laser scanning is a relatively recent technology and terrestrial applications have developed considerably in the last decade. Several types of laser scanners using different measurement principles and having different technical specifications exist (Beraldin, 2004; Fröhlich and Mettenleiter, 2004). LiDAR (light detection and ranging) laser scanners are the most suitable for geotechnical applications, as they allow measurements typically up to distances of several hundreds of metres. They use the time-of-flight technology to determine distances to an object. The point clouds obtained, after processing using reconstruction software, provide 3D models of a scene that are highly suited for geotechnical studies.

Close-range terrestrial digital photogrammetry (CRTDP) and terrestrial laser scanning (TLS) are being increasingly used to characterize rock mass discontinuity
parameters (Fig. 1-22). “Close-range” refers to a camera/scanner-object distance of up to about 300 m (Wolf and Dewitt, 2000). The potential of these techniques have been demonstrated by Feng and Röshoff (2004), Trinks et al. (2006) and Redfern et al. (2007) for terrestrial laser scanning and by Haneberg et al. (2006) and Haneberg (2008) for terrestrial digital photogrammetry. Photogrammetric packages for rock cut characterization have been presented by Birch (2006), Gaich et al. (2006) and Poropat (2006 and 2008). The accuracy of the techniques has been tested by Krosley et al. (2006), Coggan et al. (2007) and Martin et al. (2007).

Figure 1-22. Discontinuity mapping using terrestrial remote sensing techniques (after Sturzenegger et al., 2007c).

Integration of terrestrial remote sensing data into rock slope stability analysis and slope design has been undertaken by Pötsch et al. (2006), Strouth et al. (2006), Ghirotti and Genevois (2007), Mathis (2007) and Jaboyedoff et al. (2008). Underground applications are now also common (Birch, 2008; Fekete et al., 2010). Some frequently highlighted advantages are:

- the ability to sample extended windows that are not restricted to the base of an outcrop thereby providing more representative statistical samples,
- the ability to survey inaccessible steep and high rock faces,
- Risk reduction for workers as the survey can be undertaken in a remote safe location protected from traffic and rock falls,
- Creation of a permanent record of the rock slope condition at a specific time,
- Possibility to measure discontinuity orientation when conventional compass clinometer readings are affected by magnetic orebodies.

Methods allowing time efficient automated recognition of discontinuities on remote sensing 3D models (Kemeny et al., 2006; Kemeny and Donovan, 2005; Slob et al., 2005; Ferrero et al., 2009) can make these techniques even more attractive to practicing engineers, although the automation should be used with care in order to avoid orientation bias or censoring (Fig. 1-23) (Sturzenegger et al., 2007a). Monte (2004) and Lato et al. (2009) have optimized these automated methods.
The application of terrestrial remote sensing techniques for discontinuity characterization over distances larger than 300 m are limited. Abellan et al. (2006) used TLS to study rockfalls. Dunning et al. (2009) extracted landslide structural and geomorphological features. Froese et al. (2009) characterized the failure surface of a large rockslide and recognized discontinuity set orientations using the software Coltop3D (Jaboyedoff and Couture, 2003; Metzger and Jaboyedoff, 2008), which attributes a unique Red Green Blue (RGB) color for each spatial orientation (Fig. 1-24). For application on large landslides, TLS is advantageously combined with airborne LiDAR,
which is very useful for many projects requiring high resolution characterization of relatively large areas (Ruiz et al., 2003; Sturzenegger et al., 2007b).

Figure 1-24. Mapping discontinuities on a high resolution DEM of Turtle Mountain using orientation-specific color representation in Coltop3D (Froese et al., 2009; by permission).

Another important application of terrestrial remote sensing techniques in landslide studies is the monitoring of displacement and velocity, which can be undertaken using sequential 3D models. Abellán et al. (2009 and 2010) applied a single point distance routine, which is integrated in software such as Polyworks, but does not provide true 3-D displacement. The procedure to compute true 3-D displacement and velocity is to generate vectors between a selection of corresponding objects from two or more sequential 3D models (Monserrat and Crosetto, 2007; Oppikofer et al., 2008; Travelletti et al., 2008). Teza et al. (2007), and Oppikofer et al. (2009) developed more systematic approaches, using a grid of 3D model sub-areas and associated displacements. Teza et al.
(2008) further derived the strain field from the displacement field. Other applications of terrestrial remote sensing techniques on natural features or engineered slopes are listed in Table 1-2.

The increasing amount of terrestrial remote sensing applications is the result of technological advances, which have made these techniques accessible to geoscientists and geological engineers. The following chapter will review their basic principles, which should be well understood in order to ensure proper use.

Table 1-2. Non-exhaustive list of applications of terrestrial remote sensing techniques on natural features or engineered slopes.

<table>
<thead>
<tr>
<th>Publication reference</th>
<th>Technique used</th>
<th>Brief description of the application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunter et al. (2003)</td>
<td>TLS</td>
<td>Volcano activity monitoring</td>
</tr>
<tr>
<td>Rosser et al. (2005)</td>
<td>TLS/TDP</td>
<td>Quantification of rock fall volume and distribution on coastal cliffs</td>
</tr>
<tr>
<td>Bellian et al. (2005)</td>
<td>TLS</td>
<td>Creation of stratigraphic models</td>
</tr>
<tr>
<td>Tannant et al. (2006)</td>
<td>TDP</td>
<td>Surveys in open-pit mine environment</td>
</tr>
<tr>
<td>Milan et al. (2007)</td>
<td>TLS</td>
<td>Channel morphological change assessment in a proglacial river</td>
</tr>
<tr>
<td>Enge et al. (2007)</td>
<td>TLS</td>
<td>Generation of petroleum reservoir models</td>
</tr>
<tr>
<td>Pesci et al. (2007a and 2007b)</td>
<td>TLS</td>
<td>Generation of integrated TLS and airborne digital photogrammetry DEM of a volcano; volcano deformation monitoring</td>
</tr>
<tr>
<td>Deline et al. (2008)</td>
<td>TLS</td>
<td>Monitoring of permafrost-related rockfall activity</td>
</tr>
<tr>
<td>Jaboyedoff et al. (2009)</td>
<td>TLS</td>
<td>Characterization of retrogressive landslides in sensitive clay and rotational landslides in river banks</td>
</tr>
<tr>
<td>Franceschi et al. (2009)</td>
<td>TLS</td>
<td>Discrimination between marls and limestones using intensity data from TLS</td>
</tr>
<tr>
<td>Armesto et al. (2009)</td>
<td>TLS</td>
<td>Determination of the geometry of a granite boulder</td>
</tr>
<tr>
<td>Lato et al. (2009)</td>
<td>TLS</td>
<td>Monitoring of rockfall hazards using mobile terrestrial LiDAR</td>
</tr>
</tbody>
</table>

1.4 Reference list


Itasca Consulting Group, 2009b. 3DEC, version 4.1. Minneapolis, Minnesota.


CHAPTER 2
PROPOSED METHODOLOGY FOR THE
APPLICATION OF REMOTE SENSING
TECHNIQUES FOR ROCK MASS
DISCONTINUITY CHARACTERIZATION

This chapter describes the methodology developed in the thesis to perform terrestrial remote sensing surveys in the field and to generate 3D models usable for geotechnical rock mass discontinuity characterization and slope stability analyses. It is presented as a guide, which when used in combination with Appendix 1, should provide a detailed description of the procedure. The chapter first presents the basic principles and planning recommendations for close-range terrestrial digital photogrammetry and laser scanning. An important section is then devoted to presentation of the principles of varying registration approaches, including differential global positioning systems and total stations (their accuracy is subsequently evaluated in Chapters 3 and 4).

A methodology used to extend terrestrial remote sensing surveys from conventional close-range to medium- and long-range is introduced and the specific details demonstrated using three case studies. Finally, the incorporation of terrestrial remote sensing data into numerical modelling codes for slope stability analysis is discussed.

The remote sensing techniques used in this research are terrestrial digital photogrammetry (TDP) and terrestrial laser scanning (TLS). A Canon EOS 30D digital camera with a variety of lenses, whose focal length ranges from $f = 20$ to $f = 400$ mm, are used to capture digital photographs of rock slopes. Calibration of the camera and lenses is undertaken using the 3DM CalibCam software (Adam Technology, 2007). The photogrammetric software used in the construction and analysis of 3D models are 3DM CalibCam and 3DM Analyst (Adam Technology, 2007). Laser scanning is undertaken
using an Optech ILRIS-3D laser scanner (Optech Inc., 2008) and the data processed utilizing the Polyworks software package (InnovMetric Software Inc., 2006).

2.1 Terrestrial digital photogrammetry

Analytical photogrammetry is the term used to describe the rigorous mathematical calculation of coordinates of points in object space based upon camera parameters, measured photo coordinates and ground control (Wolf and Dewitt, 2000). It is based on the concept of (stereoscopic) parallax, which is the apparent displacement in the position of an object with respect to successive camera positions. In Fig. 2-1, the stereoscopic parallax of object point A is the difference between the x component of both image points a₁ and a₂. The 3D position of object point A is then measured using the relationship between its relative positions on the two images and the camera perspective centers. In other words, if the elements of exterior orientation of two cameras with perspective centers O₁ and O₂ are known, the coordinates (Xₐ, Yₐ, Zₐ) of object point A can be evaluated from measurements of the image coordinates (x₁, y₁) and (x₂, y₂) of its homologues a₁ and a₂ (Fig. 2-1) (Atkinson, 1996). This process is called “intersection”, i.e., the determination of the position in 3D space of an object point.

A process called “resection” is used to calculate the camera exterior orientation based on the image coordinates of a number of object points. The six elements of exterior orientation of a camera are the X, Y and Z positions of the perspective centers and the angles ω, φ and κ (Fig. 2-2). Resection can be achieved, using relative or absolute image coordinates of at least 7 object points (a larger number provides redundancy and the ability to detect bad points) to solve for the six elements of exterior orientation and the scale (arbitrary scale) (Adam Technology, 2007). The initial resection approximation is then refined using an algorithm known as “bundle adjustment”, which is implemented using the criteria of least squares, to determine the best estimation for the six parameters of exterior orientation of each camera (Chandler, 1999).

A crucial assumption, in both the intersection and resection processes, is the principle of collinearity, which states that an object point, the perspective center and an image point on the focal plane of the camera are aligned in a straight line (Wolf and
Dewitt, 2000). In order to respect this principle, the interior geometry of the camera during exposure must be known. Indeed, if correction for distortion and other internal parameters is not applied, collinearity will not be respected. The three main elements of interior orientation are the focal length and the \( x_0 \) and \( y_0 \) coordinates of the principal point (offset). Other parameters include lens radial (\( K_1, K_2, K_3, \ldots K_n \)) and tangential (\( P_1, P_2 \)) distortion. The interior orientation is determined during the calibration process; the procedure used for calibration (Adam Technology, 2007) is detailed in Appendix 1.

![Diagram showing the geometry for the determination of the position of an object point A.](image)

**Figure 2-1.** Geometry for the determination of the position of an object point A (after Poropat, 2001). For clarity, the right and left images are located in front of camera perspective centers.
Developments in computer performance have stimulated the creation of photogrammetry software allowing non-photogrammetrists to use this tool for a wide range of applications (Fig. 2-3). Although these software do not require a complete knowledge of photogrammetry, an understanding of the basic principles is recommended in order to guarantee good results. For further details concerning the theory of photogrammetry, the reader should refer to Slama (1980) and Atkinson (1996).

Photogrammetric software uses an automated matching process to find corresponding image points on pairs of photographs. In order to optimize the matching process, it is important to respect a number of recommendations when taking photographs (Adam Technology, 2007). These recommendations also ensure that
aperture and focus are set correctly to maintain constant focal length. A complete workflow for the creation and analysis of 3D models is presented by Adam Technology (2007).

![Workflow diagram](image)

**Figure 2-3.** Workflow for the creation of photogrammetric 3D models using Adam Technology software. The thick boxes represent data acquired in the field (calibration is partly achieved in the field).

### 2.2 Terrestrial laser scanning

Terrestrial laser scanning is defined by Lichti et al. (2008) as an active imaging system that collects range measurements in a series of horizontal and vertical increments of arc over a distance ranging from a metre to over a kilometre. Terrestrial laser scanners can be classified based on their measurement principles, which include triangulation, phase measurement or time delay (Beraldin, 2004; Fröhlich and Mettenleiter, 2004). LiDAR (light detection and ranging) laser scanners are the most suitable for geotechnical application allowing measurements up to kilometres. They use time-of-flight technology to determine distances to an object. Basic formulae relating to laser ranging have been
presented by Baltsavias (1999) and Beraldin (2004). The short wavelength, beam density and coherence allow high resolution point clouds with coordinate data and reflectance data (intensity) offering easier recognition of the object. The point cloud, through reconstruction software provides a 3D model of a scene usable for geotechnical examination.

The ILRIS-3D laser scanner (Fig. 2-4) is a compact, fully portable package. The components of the scanner include a laser, a receiver, rotating mirrors that distribute laser pulses throughout the field of view, a 6.6 megapixel digital camera and a viewfinder. The laser is a class 1 (eye safe) pulsed laser, whose wavelength is 1500 nanometres. It can scan a scene up to a distance of 1500 metres, depending on the orientation and reflectivity of the target (Table 2-1), although 800 metres will usually be the limit for scanning of rock faces. No reflector is needed.

Power is provided by a Digital HyTRON battery pack holding four mounted batteries. The power supply device allows the scanner on average to run for four to six hours. Communication with the scanner is accomplished either using a personal digital assistant (PDA) or directly via a laptop cable. Both are equipped with a controller software that allows the set up of data collection parameters such as the region of interest (ROI), mean distance and spot spacing. The scanner is mounted on a heavy duty tripod.

Before manipulation, data collected with the scanner must be extracted. The Parser software (Optech Inc., 2008) enables parsing of data, selection of an intensity value, an output format and reduction in the number of measured points. The 3D model created can then be used for visualization, merging, registration and measurements. Polyworks (InnovMetric Software Inc., 2006) is the software package selected by Optech to process ILRIS-3D data. More information about point cloud post-processing is presented in Appendix 1.
Figure 2-4. ILRIS-3D laser scanner.

Table 2-1. ILRIS-3D performance specifications (based on Optech Inc., 2008).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic scanning range</td>
<td>3 m – 1500 m to a 80% target reflectivity</td>
</tr>
<tr>
<td></td>
<td>3 m – 800 m to a 20% target reflectivity</td>
</tr>
<tr>
<td></td>
<td>3 m – 350 m to a 4% target reflectivity</td>
</tr>
<tr>
<td>Data sampling rate</td>
<td>2000 points/second</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>0.00974°</td>
</tr>
<tr>
<td>Minimum spot step (X and Y axis)</td>
<td>0.00115°</td>
</tr>
<tr>
<td>Raw range accuracy</td>
<td>7 mm at 100 m</td>
</tr>
<tr>
<td>Raw positional accuracy</td>
<td>8 mm at 100 m</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>1500 nm</td>
</tr>
<tr>
<td>Laser class (IEC 600825-1)</td>
<td>Class 1</td>
</tr>
<tr>
<td>Digital camera</td>
<td>Integrated digital camera, 6.6 megapixel (CMOS sensor)</td>
</tr>
<tr>
<td>Scanner field of view</td>
<td>40° x 40°</td>
</tr>
</tbody>
</table>
2.3 Field work planning

Before undertaking a field campaign using terrestrial remote-sensing techniques, some essential planning components should be considered. These include:

- specifying the resolution (ground point spacing) necessary for the purpose of a project,
- specifying the required accuracy and precision,
- defining the area to be mapped, taking into account physical/topographic constraints.

Careful planning allows a better understanding of the effect of these components on the subsequent geotechnical discontinuity measurements from remote sensing 3D models in terms of potential orientation bias, truncation level and observation scale effect. Measurement bias will be described in Chapters 3, 4 and 5 (Sturzenegger and Stead, 2009a and 2009b; Sturzenegger et al., in prep.). Additional general considerations concerning data acquisition, processing and accuracy, for geological applications are presented in Buckley et al. (2008).

2.3.1 Ground resolution

In a photogrammetric project, the focal length of a lens, the pixel size and the distance to an object determine the instantaneous angular field of view (IFOV), i.e., the area covered by one pixel on the ground. The ground point spacing (ground resolution) is slightly different, being dependent on the step size. Step size quantifies the number of pixels used, both horizontally and vertically, to generate one spatial point (typical step sizes range between 4 and 8 pixels). In other words, the ground pixel size (IFOV) should be multiplied by the step size to obtain the ground point spacing. In practice, the ground point spacing will also vary, due to the image quality and object surface texture.

For terrestrial laser scanning, ground resolution depends on both the laser beamwidth and spot spacing (or sampling interval). Lichti and Jamtsho (2006) combine these parameters in a measure called the effective instantaneous field of view (EIFOV). Table 2-2 shows the effective resolution that can be obtained with the ILRIS-3D laser scanner at various distances. Figure 2-5 shows that when the sampling interval (Δ) is larger than the beamwidth (δ), EIFOV is approximately equal to the sampling interval.
For example, using the Optech ILRIS-3D at 50 metres, the EIFOV is entirely defined by the sampling interval if it is larger than 20 mm. In contrast, when the sampling interval is smaller than 20 mm, the EIFOV is also influenced by the beamwidth. As a result, even though spot spacing can be decreased to a very low value, there is a physical resolution limit due to laser beamwidth. An optimal sampling interval of 86% of the beamwidth is suggested.

The beamwidth can also be referred to as the laser footprint, or the size of area averaged in a single laser beam measurement. The greater the distance to the object, the bigger the beamwidth (because of divergence of the laser beam), the bigger the footprint and consequently, the more the actual surface geometry of the target will be averaged. Horizontal and vertical footprints can be calculated using equations proposed by Giussani and Scaioni (2004). Pesci et al. (2007) show that if the angle between the beam line-of-sight and the normal to the object surface is greater than 60º, the footprint increases dramatically and more so with increasing range. Consequently, excessively oblique scans, horizontally or vertically, should be avoided. A similar logic can be used for digital photogrammetry surveys and IFOV.

It should be emphasized that the ground point spacing used in digital photogrammetry and laser scanning surveys is an average value. Due to the object topography, areas closer to the scanner have a closer ground point spacing than the average value whereas distant objects have a wider ground point spacing. Variations in ground resolution within a single remote sensing 3D model also result from other parameters, including incidence angle, reflectivity and stereomatching. As a general rule, it is suggested to use a slightly higher ground resolution than required, so that there is enough redundancy to guarantee adequate interpolation of a 3D model surface (Giussani and Scaioni, 2004).
Table 2-2. Effective instantaneous field of view ({EIFOV}) for the Optech ILRIS-3D (based on Lichti and Jamtsho, 2006).

<table>
<thead>
<tr>
<th>Range [m]</th>
<th>Angular sampling interval [mm]</th>
<th>Laser beamwidth [mm]</th>
<th>EIFOV [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.13</td>
<td>12.85</td>
<td>11.0</td>
</tr>
<tr>
<td>20</td>
<td>0.52</td>
<td>15.4</td>
<td>13.2</td>
</tr>
<tr>
<td>50</td>
<td>1.3</td>
<td>20.5</td>
<td>17.7</td>
</tr>
<tr>
<td>100</td>
<td>2.6</td>
<td>29</td>
<td>25.0</td>
</tr>
<tr>
<td>200</td>
<td>5.2</td>
<td>46</td>
<td>39.8</td>
</tr>
<tr>
<td>500</td>
<td>13</td>
<td>97</td>
<td>84.2</td>
</tr>
<tr>
<td>800</td>
<td>20.8</td>
<td>148</td>
<td>128.6</td>
</tr>
</tbody>
</table>

Figure 2-5. EIFOV versus sampling interval at 50 m range (Lichti and Jamtsho, 2006; by permission). The line EIFOV = Δ is plotted for reference.

2.3.2 Accuracy and precision

Photogrammetric stereomodel accuracy and precision depend on calibration, automated stereomatching, ground resolution and network geometry (Fraser, 1996; El-
Hakim et al., 2003). The expected planimetric accuracy is typically 0.3 pixels ([0.05-0.5]) on the ground assuming an adequate calibration and orientation (Birch, 2006). The depth accuracy depends on the geometric relationship between the camera positions and the object being photographed. Equation 2.1 (Birch, 2006) links planimetric and depth accuracy with the distance to the object and the baseline (distance between successive camera positions):

\[
\text{Depth accuracy} = \text{Planimetric accuracy} \times \frac{\text{Distance}}{\text{Baseline}}
\] (2-1)

This equation suggests that a large distance/baseline ratio provides a better depth accuracy. However, a large distance/baseline ratio results in difficulties for the image matching process. Consequently, a ratio between 5/1 and 8/1 is recommended (Fig. 2-6).

![Figure 2-6](image)

**Figure 2-6.** Geometric relationship between camera positions and the object being photographed.

Each laser scanner manufacturer provides details of precision and accuracy, which have been verified in studies by Boehler, et al. (2003), Johansson (2003), Lichti et al. (2005) and Pesci et al. (2007). Lichti et al. (2005) emphasize the importance of the uncertainty in the angular location of laser-based measurements due to the laser beam diameter (footprint). Indeed, the apparent location of the range observation is along the centerline of the emitted beam, but the actual point location cannot be predicted since it could lie anywhere within the projected beam footprint. This uncertainty can lead to an “edge effect”, which is also related to the footprint. When the laser beam moves over an edge, only a part of the laser spot is reflected, the scanner, however, interprets the received light as a whole spot (Fig. 2-7). The footprint point that has effectively produced
the reflection does not necessarily coincide with the footprint center, although the angular coordinate assigned to the reflector are those of the center (Teza et al., 2007). As a result, many erroneous points are produced which are shifted in laser direction (Boehler et al., 2001). When scanning rock slopes, the edge effect may prevent accurate survey of small scale irregularities and asperities.

![Diagram of apparent center of laser spot recorded by scanner and real center of laser spot](image)

**Figure 2-7.** Shift in the location of points at the edge of scanned objects (Boehler et al., 2001; by permission).

By far the most important factors affecting TLS/TDP 3D model accuracy and precision is the registration process into a local or global reference system. Registration can be achieved using various approaches, which will be described in Section 2.4 and evaluated in detail Chapters 3 and 4 (Sturzenegger and Stead, 2009a and 2009b).

The only truly independent and quantitative means of assessing whether the 3D model generation process has been accurate is to use some form of ground truth (Chandler, 1999). This is accomplished by comparing selected 3D model points with independently surveyed corresponding points (check points having a “true” value). To do so, it is useful to withhold a sample of the image control points for use as check points. The difference between true ($s_i$) and measured ($p_i$) values is called the “residual”.

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Accuracy is quantified by the mean error (Eq. 2.2) and highlights potential systematic errors (Lane et al., 2000). Precision quantifies the scatter, around the mean error, of repeated measurements on a 3D model. It is quantified by the standard deviation (Eq. 2.3), which highlights random errors (Lane et al., 2000).

\[
\text{Mean Error} = \sum_{i=1}^{n} (p_i - s_i) \quad (2-2)
\]

\[
\text{Standard Deviation} = \sqrt{\frac{\sum_{i=1}^{n} ((p_i - s_i) - (p_i - s_i))^2}{n}} \quad (2-3)
\]

The Earth curvature and atmospheric refraction have a negligible influence on measurements at the distances considered in this research (< 2.5 km), but should be accounted for at longer range.

### 2.3.3 Mapping area and physical/topographic constraints

Depending on the size of the area to be mapped, several scans/sets of photographs will need to be taken. Individual scans should be merged together if there is sufficient overlap between adjacent ones. For terrestrial digital photogrammetry, several model layouts, including independent convergent, image strip and image fan layouts can be used (Birch, 2006). When there are major changes in perspective, such as around a corner, the area should be split into smaller windows. When there is a potential for occlusion and/or orientation bias, separated pairs of photographs should be taken from different angles.

Occlusion occurs when parts of a rock face cannot be sampled because it is obscured by protruding features. It may create holes (shadow zones) with missing spatial points in a 3D model (Fig. 2-8a). Orientation bias occurs when the camera/scanner line-of-sight is sub-parallel to a discontinuity, resulting in a linear trace if viewed from the camera/scanner position (Fig. 2-8b). Orientation bias is reduced when the trace appears with significant relief on a 3D model. Both occlusion/orientation bias phenomena can occur horizontally and vertically (Fig. 2-8). A careful observation of rock cuts geometry and structural geology is recommended prior to applying terrestrial remote sensing techniques in order to minimize both occlusion and orientation bias.
Figure 2-8. Illustration of occlusion and vertical orientation bias (Sturzenegger and Stead, 2009a). (a) When the vertical line-of-sight of the camera/scanner is parallel to a discontinuity, there is potential for orientation bias. When the vertical line-of-sight of the camera/scanner is directed upwards at an angle steeper than a discontinuity, occlusion results in a shadow zone. (b) Rock cut view from the camera/scanner perspective, showing discontinuity traces.

Ideally, the position(s) of the camera/scanner should be chosen in order to attain the expected resolution and accuracy. In reality, topographic constraints in the field often limit the degree of flexibility in setting up a survey network. In particular, most of the rock slopes investigated can only be surveyed from below, access being limited to the foot of the mountain slopes.

Terrestrial laser scanning is physically limited by the nature of the object being scanned and its orientation relative to the scanner. The process of range measurement relies on the assumption that all light emitted will be reflected to the sensor at the air/material surface of the object. In reality, the laser beam will be subject to scattering and absorption. The parameters that control scattering are the orientation of the objects, relative to the scanner line-of-sight (angle of incidence), and roughness of the object. If
the target is not completely smooth and perpendicular to the sensor, part of the emitted light will be lost, i.e., not reflected to the sensor.

Absorption is controlled by the brightness of the target material. Lichti and Harvey (2002) show the effect of the surface material reflectivity properties on time-of-flight laser scanner measurements. The reflectivity represents the ratio between the amount of reflected and emitted signal. Reflectivity will dictate the maximum range of the laser scanner and will be discussed in Chapter 4 (Sturzenegger and Stead, 2009b). TLS will provide poor results if the weather is rainy or hazy. Similarly, TDP may be affected by poor lighting, presence of dust/steam and change in lighting conditions.

2.4 Registration approaches

TLS/TDP 3D models can be registered in a variety of coordinate systems, including the Universal Transverse Mercator (UTM) Geographic Coordinate System and relative (local) systems oriented with respect to North. The process of bringing 3D models into one of these systems is called “registration” and it can quickly become the most time-consuming part of a terrestrial remote sensing field survey. Depending on the accuracy/precision required for a specific project, various amounts of time, cost and effort are necessary and several approaches can be adopted.

This section presents the equipment used for several possible registration approaches. The details of the approaches are introduced in Chapters 3 and 4 (Sturzenegger and Stead, 2009a and 2009b). Their accuracy and precision are also evaluated in these chapters.

2.4.1 Compass

A Brunton 5010 Geo Transit compass clinometer can be used for 3D model registration, using some rapid and practical approaches.

2.4.2 Total station

A total station is a combination of an electronic theodolite (instrument with an integrated telescope to measure both horizontal and vertical angles) and an electronic
distance measuring (EDM) device. As in the case of laser scanning, the quality of distance measurements with a total station depends on the distance and reflectivity of an object. In addition, the laser beam diameter increases with the distance, resulting in averaging and potentially inducing errors.

A total station measures the coordinates \((N_i, E_i, Z_i)\) of a target from the instrument position \((N_0, E_0, Z_0)\) using trigonometry and the following equations:

\[
N_1 = N_0 + n \\
E_1 = E_0 + e \\
Z_1 = Z_0 + TS.Ht + z - P.Ht
\]

where \(n\), \(e\) and \(z\) are the prism/target center coordinates in the total station coordinate system, \(TS.Ht\) and \(P.Ht\) are the total station and prism/target heights, respectively (Fig. 2-9).

![Diagram of coordinate measuring using a total station](image)

*Figure 2-9. Coordinate measuring of a target position using a total station (after Topcon Positioning System Inc., 2008).*

The instrument used in this research is a Topcon GPT-3002LW long range reflectorless total station (Topcon Positioning System Inc., 2008). Some specifications are listed in Table 2-3.
Table 2.3. Topcon GPT-3002LW total station specifications (based on Topcon Positioning System Inc., 2008) (2 mm + 2 ppm x D = 2 mm + 2 mm per kilometre of distance).

<table>
<thead>
<tr>
<th></th>
<th>Prism mode</th>
<th>Reflectorless mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement range</td>
<td>3000 m</td>
<td>1200 m</td>
</tr>
<tr>
<td>Range measurement accuracy</td>
<td>2 mm + 2 ppm x D</td>
<td>10 mm + 10 ppm x D</td>
</tr>
<tr>
<td>Angle measurement accuracy</td>
<td>2 arcsec</td>
<td>2 arcsec</td>
</tr>
</tbody>
</table>

2.4.3 Differential Global Positioning System

By tracking the microwave radio signal that Global Positioning System (GPS) satellites are transmitting continuously, a GPS can calculate the latitude, longitude and height of a receiver. The principle is illustrated in Fig. 2-10. On this figure in two dimensions, three distances from three satellite positions are required to determine a unique receiver position, the equal-distance trace to a fixed point (satellite) being a circle. In three dimensions, to find a unique receiver position, four satellites and four distances are required, the equal-distance trace to a fixed point being a sphere.

There is an additional unknown as the receiver clock is usually different from the GPS clock, consequently, an additional satellite is required, i.e., five in total. However, by using only four satellites, two possible solutions can be obtained, one being in space which can thus be neglected. Consequently, four satellites are required to satisfy four unknowns, the X, Y and Z coordinates and the receiver clock delay. Additional satellites allow redundancy. A detailed presentation of the equations to calculate the receiver position from the satellite positions (ephemeris), satellite distance (pseudorange derived from code or carrier phase) as well as a presentation of the structure of the GPS and the acquisition and tracking of the signal can be found in Tsui (2005). The following sections provides basic information necessary for the application of DGPS technology to register 3D models. The results of a specific test are also presented.
Figure 2-10. Definition of the unique receiver position in 2D, knowing three satellites positions (S1, S2, S3) and three distances (x1, x2, x3) (Tsui, 2005; by permission).

2.4.3.1 Geodetic principles

The fact that the topographic surface of the Earth is highly irregular makes it difficult for geodetic calculations. To overcome this problem, geodesists adopt a smooth mathematical surface called an “ellipsoid”, to approximate the Earth surface. In North America, a common ellipsoid (or horizontal datum) is the North American Datum of 1983 (NAD83). The World Geodetic System from 1984 (WGS 84) is another datum usable worldwide.

The vertical datum, i.e., the surface of zero height, is often the geoid (equipotential surface, along which the gravity potential is constant). On a global basis, it represents the mean sea level. The height above or below the geoid is called “orthometric height”. GPS obtained heights are referred to the ellipsoid and are called the “ellipsoidal heights”. Many GPS receivers and software packages have built-in models for automatic conversion between orthometric height and ellipsoidal height.
GPS data are measured in a three-dimensional geodetic coordinate system (latitude, longitude, height). Map projection is the transformation of the geodetic coordinates into rectangular grid coordinates (northing, easting, height) or Cartesian coordinates (x, y, z). The projection should minimize the distortion due to transforming an ellipsoidal shape to a flat surface. The Universal Transverse Mercator (UTM) is the most common map projection. The Earth ellipsoid is divided into 60 zones, which are projected separately, using a secant cylinder. It is not suitable for the polar areas, where the projection results in significant distortion.

2.4.3.2 Differential positioning

Positioning can be both absolute and relative (differential). Using absolute positioning, i.e., using a single receiver, the accuracy is on the order of metres or tens of metres, due to the large distance between the satellites and the antenna, the small magnitude of the time increments and other systematic errors (Gili et al., 2000; El-Rabbany, 2006). The accuracy also depends on whether the receiver is a single L1 frequency or a dual L1 and L2 frequency GPS.

Using relative (or differential) positioning, i.e., two or more receivers, an accuracy of a few metres to millimetres can be obtained (El-Rabbany, 2006). Usually, one receiver, called the base, is positioned at a known point or left on a point for a long time, so that its position is recorded with accuracy. Another receiver, called the rover, is placed at the position, which is to be surveyed. By simultaneously tracking the same satellites, the base and rover are subject to the same errors and bias. The known position of the base is used to calculate corrections to the GPS derived position and these corrections are subsequently applied to the rover (Hofmann-Wellenhof et al., 2001). The shorter the distance between base and rover receivers, the more similar the errors.

When there is redundancy of measurement, least-square adjustments can be applied on survey observations (angles, distances, elevation differences and vectors) in order to refine position calculations (Thales, 2005).

Various field measurements methods exist for differential surveys:
• Static survey (highest precision) requires measurements for at least 30 minutes at each rover position, depending on the baseline length (typically less than 30 km), the number of satellites and their geometry. Periodic loss of satellites should not affect the survey. Post-processing is necessary.

• FS (Fast static) survey is a development of the classical static method, with improved algorithms that speed the procedure (Table 2-4) (Blewitt et al, 1989; Frei and Beutler, 1990). The rover(s) recording interval should be reduced to about 5 seconds. Post-processing is necessary.

Table 2-4. Typical time required at each receiver position during a fast static survey.

<table>
<thead>
<tr>
<th>Number of satellites available</th>
<th>Time of logging required [min.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 or more</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
</tr>
</tbody>
</table>

• RTK (Real Time Kinematic) method merges the information of code and carrier phase observables received at both base and rover receivers and instantaneously computes the precise position (Quirion, 1993). The RTK method calculates new positions from the old ones, through continuous tracking of the satellites in real time. Consequently, although post-processing is not required, the system must be initialized and direct line-of-sight between rovers and the base is necessary.

• Stop-and-go survey (semi-kinematic technique) uses rover measurements performed over about 30 seconds. The recording interval should be reduced to about 1 second. This method requires initialization, and 4 satellites must be continuously tracked, otherwise re-initialization has to be done.

Measurement errors can have different forms. Gross errors results from human mistakes such as station misidentification, inaccurate antenna height measurements or introduction of wrong survey monument point coordinates. Imprecision and inaccuracy result from the quality of the receivers and antennas, the observation procedure and its duration. Finally, errors can result from the algorithm used during post-processing. Typical total rover errors for X and Z coordinates using the FS method are 12 mm (max. 30 mm) and 26 mm (max. 46 mm), respectively, assuming an optimal survey method.
2.4.3.3 DGPS for geotechnical applications

Fieldwork in remote areas or at specific outcrops sometimes renders it impossible to find survey monuments, with known coordinates, to set up the base station. In addition, survey time at individual outcrops usually spans over a few hours to a day, which precludes surveying a base station for a longer time. Consequently, the position accuracy of the base station can be limited. To overcome this problem, various alternatives can be used and were tested.

- Alternative 1: the base receiver is located on a survey monument with known coordinates (seed coordinates). Lists of existing survey monuments in Canada are available, including Canada Base Network (CBN1), Primary Vertical Bench Marks (PVBMC1) and Federal 3D Densification Network (FED3DC1) (www.geodiscover.cgdi.ca). This is the optimal survey setting presented in the previous section.

- Alternative 2: the survey in the field is restricted to measurements with the rover receiver. Available continuous GPS stations provided by global or regional services are used as base measurements for post-processing of the rover data. Although regional surveys may be distant from the field site, they can provide abundant and accurate measurements (10 days or more of survey). Continuous regional surveys can be found at:
  - www.unavco.org (global),
  - IGS network: http://igscb.jpl.nasa.gov (global),
  - CORS: http://www.ngs.noaa.gov/CORS (North America),
  - CACS: Canadian Active Control System (CACS) (http://www.geod.nrcan.gc.ca/index_e.php or www.geodiscover.cgdi.ca),

- Alternative 3: the base receiver is located at an unknown point and logged for a period as long as possible. The rover receiver surveys the locations of interest. Although the survey accuracy is lower, due to the lack of known base receiver coordinates, the shift of the measured values with respect to the true position will be approximately constant for all the receivers (Gilbert, 1995): base and rover receivers
may not thus be accurately positioned, although correctly oriented. In many cases, such a setting is adequate for geological applications. Note that for more accuracy, use of post-processed “precise ephemerides” and “satellite clock corrections” provide a more accurate estimation of the satellites positions and ranges, respectively, for the calculation of receivers’ positions.

2.4.3.4 Accuracy test

The accuracy of the various GPS survey alternatives previously presented has been tested in the Burnaby Mountain Park, near Simon Fraser University. The unit used is a single frequency Thales Promark3 DGPS (Thales Group, 2008). During the test, base and rover receivers were positioned on survey monuments (City of Burnaby, 2007), so that the survey could be compared with known values of northing, easting and elevation (Table 2-5). The data were post-processed using the software GNSS Solutions (Thales Group, 2008). Conversion from ellipsoidal height (NAD83) to orthometric height (CVD28) was done using the software GPS-H (Canadian Geodetic Service, 1998). For alternative 2, an active control point, provided by CACS, was available in Chilliwack, BC, about 70 km to the south-east. Alternatives 1 and 3 were tested by recording the base location over various periods of time (Fig. 2-11b and 2-11c).

Table 2-5. Survey Monuments data (based on City of Burnaby, 2007).

<table>
<thead>
<tr>
<th>GCM No</th>
<th>921197</th>
<th>311001</th>
<th>357186</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>76H3771</td>
<td>76H3772</td>
<td>6059</td>
</tr>
<tr>
<td>Elevation</td>
<td>287.72</td>
<td>293.643</td>
<td>297.512</td>
</tr>
<tr>
<td>UTM North</td>
<td>5458797.389</td>
<td>5458935.162</td>
<td>5458793.859</td>
</tr>
<tr>
<td>UTM East</td>
<td>504681.639</td>
<td>504813.926</td>
<td>504760.367</td>
</tr>
<tr>
<td>SF Combined</td>
<td>0.9995581</td>
<td>0.9995572</td>
<td>0.9995566</td>
</tr>
<tr>
<td>Latitude</td>
<td>49°16’54.884022”</td>
<td>49°16’59.34178”</td>
<td>49°16’54.767527”</td>
</tr>
<tr>
<td>Longitude</td>
<td>12°25’68.263845”</td>
<td>122°56’1.70979”</td>
<td>122°56’4.367025”</td>
</tr>
<tr>
<td>Datum</td>
<td>NAD83 (CSRS) 2005</td>
<td>NAD83 (CSRS) 2005</td>
<td>NAD83 (CSRS) 2005</td>
</tr>
<tr>
<td>Horizontal datum</td>
<td>NAD83 (CSRS) 4.0.0.BC.1</td>
<td>NAD83 (CSRS) 4.0.0.BC.1</td>
<td>NAD83 (CSRS) 4.0.0.BC.1</td>
</tr>
<tr>
<td>Vertical datum</td>
<td>CVD28 GVRD</td>
<td>CVD28 GVRD</td>
<td>CVD28 GVRD</td>
</tr>
<tr>
<td>Status</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
</tbody>
</table>
The results of the test are presented in Fig. 2-11. Accuracy is quantified by the residual, which represents the difference between the measured and known positions. As expected, alternative 1 is the most accurate and alternative 3 the least accurate. Alternative 2 is only slightly less accurate the alternative 1. Horizontal accuracy (Fig. 2-11a) is greater than vertical accuracy (Fig. 2-11b) for all alternatives. Using alternative 3, the residuals are quasi-constant in magnitude and direction. Consequently, although this setting cannot provide a high position accuracy, it provides accurate measurements of orientations and distances.

Figure 2-11d shows that both horizontal and vertical accuracy increases significantly, when the time of survey at the base station increases, using alternative 3. This trend is not as marked using alternative 1, the accuracy being already high (about 4 cm) after 2 hours of survey (Fig. 2-11c). Most importantly, Fig. 2-11d show that xy residuals for both base and rovers are constant, which is consistent with the statement of Gilbert (1995), quoted previously, that the shift of the measured values with respect to the true position will be approximately constant for all the receivers. On the other hand, elevation measurements are much less predictable and the results suggest that, using alternative 3, the base station should be surveyed for a minimum of 4 hours.

2.4.4 Pre-registered 3D models

TLS/TDP 3D model registration can be achieved using 5-10 recognizable features on a pre-registered 3D model. For example, it is possible to use a general 3D model created using low resolution (\( f = 50 \) mm) terrestrial digital photogrammetry and use the coordinates of recognizable features to register higher resolution (\( f = 200-400 \) mm) 3D models. This approach is convenient, because low resolution 3D models require less photographs/scans and less survey targets than higher resolution ones. It has been applied at the Palabora open-pit mine and more details can be found in Appendix 2 (Sturzenegger et al., 2009).

It is possible to use airborne Digital Elevation Models (DEMs) and apply the same procedure. The accuracy may be relatively low, because of the DEMs relatively low resolution and the difficulty in precisely recognizing 5-10 features. A better alternative,
using airborne DEMs, may be to use the best-fit alignment option available in Polyworks to align airborne DEMs together with the photogrammetric 3D models. This approach has been applied at the Chehalis Lake rockslide (Brideau et al., 2010), and more details can be found in Appendix 1.
Figure 2-11. DGPS accuracy test at the Burnaby Mountain Park. (a) Horizontal accuracy using alternative A1-A3, (b) vertical accuracy using alternative A1-A3, (c) alternative 1 accuracy versus time of base survey, (d) alternative 3 accuracy versus time of base survey.

2.5 Porteau Cove Rockslide case study

The Porteau Cove rock cut is located along Highway 99, 40 km north of Vancouver, and is the location of a 16000 m$^3$ rockslide, which occurred in July 2008. Its
location along a fjord with steep slopes made the survey challenging, because of the lack of space to locate the laser scanner and the camera. Such a setting made it impossible to survey the upper part of the rock cut, because of vertical occlusion and very oblique line-of-sight (Fig. 2-12). Consequently, only the lower part of the cut could be surveyed with the terrestrial laser scanner (TLS) and it was decided to survey the rest of the slope using terrestrial digital photogrammetry (TDP), from a boat on the fjord.

![Figure 2-12. Porteau Cove rock cut survey setting.](image)

Because of the movement of the waves affecting the boat, the laser scanner could not be used (although motion compensation equipment has recently been developed by Optech) and TDP with $f = 50$ and $f = 100$ mm lenses was the optimal survey choice. The baseline distance was approximately 30 m, however, this was difficult to estimate accurately, because the boat was drifting as the photographs were taken. A handheld GPS was used to locate the approximate camera positions.

No tripod could be used on the boat, again because of the movement of the waves, so the photographs were taken handheld, being careful to keep the camera as stable as possible. In such a situation, it is recommended to take enough sets of photographs in case some lack focus and in order to obtain an optimal baseline-distance ratio.
Registration was obtained by using the pre-registered ground TLS imagery obtained at the base of the rock cut (which was itself registered using simple compass measurements – approach A in Chapter 3). The final composite TLS/TDP 3D model is shown on Fig. 2-13.

Figure 2-13. Detail of the Porteau Cove composite TDP and TLS 3D model, showing the failure surface of the July 2008 rock slide (white surface on the picture).

2.6 Medium and long-range terrestrial remote sensing case studies

An important part of this research has included the development of guidelines for medium and long-range terrestrial remote sensing surveys. The general approach is similar to the methodology applied for close-range remote sensing, which has been presented in this chapter.

In this research, terrestrial laser scanning could only be used for close- and medium-range terrestrial remote sensing projects, because the reflectivity of rocks limit its range to approximately 800 m. The Optech ILRIS-3D enhanced range option may increase this distance to 1000 m and other laser scanner manufacturers may increasingly offer products allowing surveys at longer range. Terrestrial digital photogrammetry is more flexible at medium- and long-range, but requires the use of large focal length lenses
in order to obtain adequate ground resolution. The use of large focal length lenses presents some challenges, in particular concerning their calibration.

Long-range terrestrial digital photogrammetry has been applied at the Palabora open-pit mine. The field procedure and some preliminary discontinuity characterization results are summarized in Appendix 2 (Sturzenegger et al., 2009). Turtle Mountain was also chosen as a test location for the application of terrestrial remote sensing techniques for mapping of a large landslide. The field procedure is detailed in Appendix 3 and the detailed 3D model processing is described in Appendix 1. Preliminary observations were summarized in a conference paper (Sturzenegger et al., 2007) and the final results included in Chapter 4 (Sturzenegger and Stead, 2009b).

2.7 Incorporation of terrestrial remote sensing data into slope stability analysis

Depending on the complexity of the method/code for slope stability analysis, various discontinuity parameters need to be incorporated. Basic kinematic and limit equilibrium analysis require specific discontinuity geometric properties and rock slope geometry measurements (Table 2.6). Discontinuity position, dip, dip direction and persistence can be directly obtained from 3DM Analyst. Using Polyworks, dip and dip direction are derived from the planes direction cosines (see Appendix 1). Discontinuity roughness and curvature can be measured using the methods summarized in Chapter 3 (Sturzenegger and Stead, 2009a).

Quantitative information on rock slope geometry, including orientation and height can be readily measured. Cross sections can be generated and the volume of unstable/fallen blocks estimated. A method to measure the volume of rockslide debris and subsequently reconstruct the pre-slide morphology is detailed in Chapter 6. This approach can also be applied to estimate the volume of unstable blocks if the structure of a rock slope is sufficiently well understood. These procedures are explained in Appendix 1.

More advanced software require the estimation of discontinuity frequency and/or block size/shape (Table 2-6). Chapter 5 (Sturzenegger et al., in prep.) describes
quantification of these parameters using remote sensing circular sampling windows and discrete fracture network (DFN) models. The procedure is detailed in Appendix 1. A description of the various types of methods for slope stability analysis is beyond the scope of this research. Their use will be limited to basic examples illustrating the incorporation of remote sensing data. Examples will be given in Chapters 3, 5 and 6.

Table 2-6. Remote sensing data incorporated into various types of slope stability analysis.

<table>
<thead>
<tr>
<th>Discontinuity parameters</th>
<th>Kinematic analysis</th>
<th>Limit equilibrium analysis</th>
<th>Continuum modelling</th>
<th>Discontinuum modelling</th>
<th>DFN model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Dip/Dip Direction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Sets</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Persistence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Roughness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Block size/shape</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Slope orientation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope geometry (2D cross section, height, 3D topography, volume/area)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following chapters will describe how to optimize the use of remote sensing techniques to characterize rock mass discontinuities and rock slope geometry and how to incorporate these remote sensing-based data into rock slope stability analysis.

2.8 Reference list


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CHAPTER 3
CLOSE-RANGE TERRESTRIAL DIGITAL PHOTOGRAMMETRY AND TERRESTRIAL LASER SCANNING FOR DISCONTINUITY CHARACTERIZATION ON ROCK CUTS

The following chapter has been published as:

3.1 Abstract

This chapter reviews the application of close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Terrestrial remote sensing techniques are being increasingly used as a complement to traditional scanline and window mapping methods. They provide more comprehensive information on rock cuts, allow surveying of inaccessible outcrops, and increase user safety. Selected case studies are used to estimate the accuracy of several 3D model registration approaches and the most time-, effort- and cost-effective methods are highlighted. It is shown that simple registration networks are able to provide adequate measurement of discontinuity orientation for engineering purposes. The case studies presented also illustrate the effects of sampling bias and limitations related to discontinuity characterization using remote sensing techniques. Vertical orientation bias and occlusion can be of particular concern when persistent discontinuities dip at the same angle as the camera/scanner line-of-sight. Major advantages of the techniques are presented illustrating how terrestrial remote sensing techniques provide rapid spatial measurements of discontinuity location, orientation and curvature and are well suited to the quantification of persistence magnitudes greater than 3 metres.
3.2 Introduction

Close-range terrestrial digital photogrammetry (CRTDP) and terrestrial laser scanning (TLS) are being increasingly used as mapping tools to describe the morphology of natural and engineered rock slopes in 3D. “Close-range” refers to a camera/scanner-object distance of up to about 300 m (Wolf and Dewitt, 2000). Several authors have recognized the potential of these techniques for rock slope characterization (Feng and Röshoff, 2004; Haneberg et al., 2006; Jaboyedoff et al., 2008; Lato et al., 2009; Monte, 2004; Redfern et al., 2007; Tonon and Kottenstette, 2007; Trinks et al., 2006). Some frequently highlighted advantages are:

- the ability to sample extended windows that are not restricted to the base of an outcrop thereby providing more representative statistical samples,
- the ability to survey inaccessible steep and high rock faces,
- risk reduction for workers as the survey can be undertaken in a remote safe location protected from traffic and rock falls,
- creation of a permanent record of the rock slope condition at a specific time,
- allow discontinuity orientation measurements when conventional compass clinometer readings are affected by magnetic orebodies.

Methods allowing time efficient automated recognition of discontinuities on 3D models (Kemeny et al., 2006; Kemeny and Donovan, 2005; Slob et al., 2005; Ferrero et al., 2009) can make these techniques even more attractive to practicing engineers. The user must always consider sampling bias, particularly orientation bias, and the current limitations of automated recognition applied to both trace mapping and measurements on highly irregular joint surfaces.

The use of analytical photogrammetry in rock cut analysis was of limited extent in the past, however, recent developments in computer performance and increased use of digital photographs have stimulated advances in photogrammetric software allowing rapid construction of 3D models. Consequently, CRTDP has become available to non-photogrammetrists and is finding widespread application in geotechnical engineering. For further details concerning the theory of analytical photogrammetry, the reader should refer to Slama (1980) and Atkinson (1996).
Unlike analytical photogrammetry, laser scanning is a relatively recent technology, and terrestrial applications have developed considerably in the last decade. Several types of laser scanners using different measurement principles and having different technical specifications exist (Beraldin, 2004; Fröhlich and Mettenleiter, 2004). LiDAR (light detection and ranging) laser scanners are the most suitable for geotechnical application, as they allow measurements typically up to distances of several hundreds of metres. They use the time-of-flight technology to determine distances to an object. The point clouds obtained, after processing using reconstruction software, provide 3D models of a scene that are highly suited for geotechnical studies.

Discontinuity characterization represents a major component of rock cut analysis including determination of discontinuity geometric properties, such as spatial location, orientation, size and roughness (ISRM, 1978). Traditional discontinuity characterization is achieved using scanline and window survey techniques (Priest, 1993).

The purpose of this chapter is to review and evaluate existing methods for rock mass discontinuity characterization using CRTDP and TLS. The evaluation is based on surveys of selected rock cuts in a variety of rock types. The accuracy of five 3D model registration approaches is quantified, followed by a discussion on ground resolution and occlusion. Discontinuity mapping on 3D models, using manual delineation of discontinuities is then evaluated. Specific advantages of CRTDP and TLS techniques in rock slope discontinuity characterization are highlighted, and issues related to observation scale, sampling bias and rock mass texture are discussed.

3.3 Methodology

3.3.1 Close-range terrestrial digital photogrammetry and terrestrial laser scanning

Field work presented in this chapter includes a program of CRTDP, TLS and conventional scanline surveys. A Canon EOS 30D digital camera with a 50 mm focal length lens was used to capture digital images of the rock cuts (Fig. 3-1b). Calibration of the camera and lens, construction of 3D models and discontinuity measurements were all achieved using the 3DM CalibCam and 3DM Analyst software (Adam Technology, 2007). Laser scanning was undertaken using an Optech ILRIS-3D (Optech Inc., 2008)
(Fig. 3-1a) and data processing utilizing the Polyworks software package (InnovMetric Software Inc., 2006).

Figure 3.1. Field equipment. (a) Optech ILRIS-3D Laser scanner, (b) Canon EOS 30D digital camera with 50 mm lens, (c) Brunton 5010 Geo Transit compass, (d) Thales Promark3 Differential Global Positioning System, (e) Topcon GPT-3002LW long range reflectorless Total Station.
3.3.2 Site description

Table 3-1 provides details of the five highway rock cuts surveyed in this study using both CRTDP and TLS and Fig. 3-2 shows their location in British Columbia and Alberta, Canada. A variety of rock types was selected in order to include intrusive, metamorphic and sedimentary rock types of varying Geological Strength Index (i.e., blockiness and rock mass strength) (Fig. 3-3). Rock cuts are typically less than 40 m high. The lengths of the rock cuts similarly range from 40 m to 150 m. In this study, the distance between the camera/scanner station and the rock slope face is between 30 m and 160 m being constrained by site specific details such as road width and visibility.

Figure 3-2. Sketch map showing locations of surveyed rockcuts. “a” to “e” refer to sites described in Table 3-1 and Fig. 3-3.
Table 3-1. Details of rock cuts investigated.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Rock type</th>
<th>Age</th>
<th>GSI - structure</th>
<th>Rock cut height/length</th>
<th>Average slope dip/dip direction</th>
<th>Average range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murrin Lake</td>
<td>50 km north of Vancouver (Canada), along Highway 99</td>
<td>Granodiorite from the Coast Plutonic Complex (Massey et al., 2005)</td>
<td>Mid-Cretaceous</td>
<td>[85-95] - massive</td>
<td>37/41</td>
<td>80/328</td>
<td>163</td>
</tr>
<tr>
<td>Mount Seymour</td>
<td>North of Vancouver (Canada), along the road leading to the Mount Seymour ski resort</td>
<td>Quartz diorite intrusive rock from the Coast Plutonic Complex (Massey et al., 2005). Some younger basaltic dykes intrude the rock mass in its central and southwestern part</td>
<td>Mid-Cretaceous</td>
<td>[60-70] - blocky</td>
<td>19/80</td>
<td>74/137</td>
<td>31</td>
</tr>
<tr>
<td>Manning Park</td>
<td>Manning Provincial Park, 170 km east of Vancouver, along Highway 3</td>
<td>Slate with lenses of sandstone from the Jackass Mountain Group (Massey et al., 2005)</td>
<td>Lower Cretaceous</td>
<td>[40-50] - schistose</td>
<td>14/120</td>
<td>70/200</td>
<td>29</td>
</tr>
<tr>
<td>Saskatchewan Crossing</td>
<td>10 km south of Saskatchewan Crossing, Canadian Rocky Mountains, along Highway 93</td>
<td>Limestone and derived dolomite from the Eldon Formation (Aitken, 1968)</td>
<td>Middle Cambrian</td>
<td>[65-75] - blocky</td>
<td>13/70</td>
<td>73/074</td>
<td>30</td>
</tr>
<tr>
<td>Lake Louise</td>
<td>Lake Louise, Canadian Rocky Mountains, along Highway I</td>
<td>Rusty weathering, silty, green to grey slate unit, part of the Miette Group (Carey and Simony, 1985; Aitken, 1969)</td>
<td>Late Proterozoic</td>
<td>[15-25] - schistose</td>
<td>21/150</td>
<td>60/209</td>
<td>37</td>
</tr>
</tbody>
</table>
Figure 3-3. Rock cuts investigated (see Fig. 3-2). (a) Murrin Lake, (b) Mt Seymour, (c) Manning Park, (d) Saskatchewan Crossing, (e) Lake Louise.
3.3.3 Image registration

The final accuracy of a 3D model is a function of the quality of the image registration process (other parameters are listed in Section 3.4). Different approaches can be adopted to register images in a 3D model dependent on whether registration is required in an absolute coordinate system or in a relative system oriented with respect to North. Surveying instrumentation used in the current study is shown in Figs. 3-1c, 3-1d and 3-1e and includes a Topcon GPT-3002LW long range reflectorless Total Station (TS) (Topcon Positioning System Inc., 2008), a single frequency Thales Promark3 Differential Global Positioning System (DGPS) (Thales Group, 2008) and a Brunton 5010 Geo Transit compass clinometer. The total station can provide millimetre accuracy, the DGPS an absolute or relative positional accuracy in the order of a few centimetres and the compass an angular measurement up to 1°.

A number of approaches (A-E) can be used to register 3D models varying in terms of setup (time), and equipment required (cost). The simplest ones (approaches A and E) use compass clinometer readings allowing registration in a relative reference system oriented with respect to North. The setup is quick, easy and inexpensive. On the other hand, approaches B, C and D use a total station and/or DGPS, which requires a longer and more expensive survey. When access to a rock cut is limited, approaches A and B are very convenient.

The choice of the registration approach depends on the accuracy demanded and the time, effort and cost constraints. Accuracy will be evaluated and discussed further in Section 3.4.1. Table 3-2 and Fig. 3-4 describe and illustrate respectively approaches A to E for 3D model registration.
<table>
<thead>
<tr>
<th>Approach</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>The line-of-sight of the camera/laser scanner is measured with a compass. The scale is provided through measurement of the distance between the two camera positions. The tilt must be zeroed. This field setting is cost and time effective, since it does not require any survey and is convenient if access to the rock cut is not possible. The use of a tripod is necessary. Compass measurements can be affected in the presence of a magnetic body.</td>
</tr>
<tr>
<td>B</td>
<td>Three sets of photographs are taken from three surveyed camera positions. The expected accuracy of the 3D model is slightly lower (about 0.3 pixel). The reason is that all photographs are assumed to be taken from the three surveyed locations. These locations should represent the positions of the perspective center of the camera and rotating center of the camera tripod. However, there is a slight unknown offset between the assumed and true perspective center (Adam Technology, 2007), which results in a slight change in its actual position, when the camera is rotated to cover entire outcrops, using an image fan model layout. With this approach, no control point is located near the rock cut. Consequently, the survey will be extrapolated from the camera location, which can propagate errors in their position measurements. This field setting is useful if access to the rock cut is not possible. The survey is performed using either the total station or the DGPS. The use of a tripod is necessary to keep the camera at constant location. This approach can also be used with the laser scanner.</td>
</tr>
<tr>
<td>C</td>
<td>Six or more targets are located on a rock cut and surveyed with the total station. Three targets are necessary, but additional ones optimize their spatial distribution and provide redundancy (i.e., increase reliability). This approach represents the optimal setting, but it requires more time and effort to set up and survey the targets. A total station must be available. No camera/scanner position needs to be surveyed, which provide flexibility for its location.</td>
</tr>
<tr>
<td>D</td>
<td>One surveyed control point is located in the field of view in addition to two surveyed camera stations (CSIRO, 2007). Control point and camera positions are surveyed using either the total station or the DGPS. The control point should be located as close to the rock cut as possible, depending on access and hazard. The use of a tripod is necessary.</td>
</tr>
<tr>
<td>E</td>
<td>Three targets are located at right angles indicating the z and x (or y) axis of a local reference system (Gaich et al., 2006). The x (or y) axis are aligned with the North (or East) using a compass. The distance between two targets is measured to provide the scale. The whole network is located as close to the rock cut as possible, depending on access and hazard. This field setting is cost and time efficient, since no survey is necessary. Compass measurements can be affected in the presence of a magnetic body.</td>
</tr>
</tbody>
</table>
3.4 3D model quality and survey planning

Planning a photogrammetric rock cut survey requires three essential components:

- specification of the accuracy and precision required for mapping,
- specification of the required resolution (ground pixel size),
- definition of the area to be mapped considering the physical constraints and the potential for occlusion problems.

Some additional general considerations concerning data acquisition, processing and accuracy, for geological applications are presented in Buckley et al. (2008).

As discussed previously, accuracy of 3D models is mainly dependent on the registration approach used for a project. In addition, accuracy depends on several factors including registration, calibration, imaging quality, resolution, and network geometry. To a lesser extent, photogrammetric stereomodels can be affected by stereomatching performance and the degree of interpolation (Lane et al., 2000). The quality of a photograph is directly controlled by the quality of the lens and the sensor resolution (number of pixels). Optimal settings for image capture and network geometry are
specified by Birch (2006) and more details can be found in Fraser (1996) and El-Hakim et al. (2003).

The quality of TLS point clouds is controlled by the roughness and brightness of the object being scanned and its orientation relative to the scanner line-of-sight. These parameters can result in both scattering and absorption of the laser beam. Laser scanner accuracy and point cloud artifacts have been investigated by Boehler et al. (2003), Johansson (2003) and Lichti et al. (2005).

3.4.1 3D model accuracy evaluation

Accuracy and precision are obtained by comparing the position on 3D models of 6 to 8 targets (northing, easting and elevation) with their position surveyed independently using the total station. Because of its high performance, the total station measurement is considered as the reference or true value. Accuracy highlights potential systematic errors, while precision represents random errors (Lane et al., 2000). Accuracy evaluates how close each measured value is to its associated true value. The difference between true and measured value is called the “residual”. Accuracy is quantified by the mean error (ME), which is the sum of the residuals divided by their number. Precision quantifies the scatter, around ME, of repeated measurements on the 3D models. It is quantified by the standard deviation of error (SDE).

To check discontinuity orientation measurements accuracy on 3D models, the orientation of 6 to 10 selected reference discontinuities were measured in the field with a compass clinometer and then compared to the orientation measurements obtained on 3D models derived from remote sensing. In order to provide representative results, both sub-horizontal and sub-vertical reference discontinuities were selected and measurements undertaken using both discontinuity surfaces and traces. In order to account for the influence of waviness, compass clinometer measurements were performed at different locations along each selected discontinuity, plotted on a stereonet and contoured (Dips, Rocscience Inc., 2003) to provide a mean value of dip and dip direction. Discontinuity orientation measurements obtained from 3D models are the result of the averaging of a selection of points, which are coplanar and distributed on a recognizable surface or along
a discontinuity trace. Residuals represent the difference between compass and 3D model measurements.

Accuracy was evaluated at the Mount Seymour, Saskatchewan Crossing and Lake Louise rock cuts (Figs. 3-3b, 3-3d and 3-3e and Table 3-1). At each location, seven 3D models were generated, using various combinations of CRTDP, TLS and registration approaches A to E (Table 3-2). A total station was used to survey targets and camera/scanner positions, except for the case of registration approach D at the Mount Seymour rock cut, where the DGPS was used to survey both camera and control point positions. Photographs were taken with an image fan model layout (Birch, 2006).

3.4.1.1 Point accuracy results

A comparison of accuracy and precision of the seven 3D models generated at the three rock cuts is presented in Fig. 3-5. As expected, registration using approach C provides the highest accuracy (lowest ME) and precision (lowest SDE). The results are consistent with the ones obtained by Krosley et al. (2006) and Martin et al. (2007). The use of CRTDP or TLS does not influence the results significantly. Laser scanners may not point directly to the centre of a target. Consequently, the target coordinates must be estimated by centroiding a carefully selected neighbourhood of samples that cover the surface of the target. This can result in a spatial error known as the target reduction error (Gordon and Lichti, 2004). Other possible sources of uncertainty can be related to the total station survey, the performance of the camera/scanner and the software (matching, extrapolation, resection, etc). More details can be found in Birch, (2006), Beraldin (2004), Boehler et al. (2003), El-Hakim et al (2003), Johansson (2003) and Lichti et al. (2002).

Approach D is only slightly less accurate than C. Northing and elevation residuals are observed to be high at the Mount Seymour rock cut in marked contrast to the very low values determined at the other outcrops. This result is explained by that fact that, at this location, approach D registration was achieved with the DGPS, instead of the total station used at the other rock cuts. The expected accuracy of the DGPS survey is centimetric to decimetric, providing lower accuracy than the total station. However, the mean error is constant in magnitude and direction (Gilbert, 1995). Consequently,
although not accurately positioned, (with respect to absolute coordinates) the 3D model is correctly oriented and discontinuity orientation measurements are not affected (Fig. 3-6).

The result of approach D shows how a single control point in the field of view improves the accuracy of a 3D model, compared to approach B, which is registered only using the camera/scanner positions. Approach B is consistently less accurate and precise than both approaches C and D, for the reason explained in Table 3-2. Another source of error, specific to approaches B and D, is the positioning of the camera at the exact position, which was previously surveyed using total station or DGPS, and the measuring of camera height.

The accuracy of approaches A and E is meaningless, because they do not provide registration in the same coordinate system as the surveyed targets. Only the precision can be evaluated. Figure 3-5 shows that both approaches are significantly less precise than the alternative methods. In addition, the magnitude of imprecision seems to be less consistent on the three rock cuts. Since imprecision can be attributed to compass readings, this study shows how sensitive the precision of a 3D model is, when it is registered using compass readings alone. Consequently, when using approaches A and E, it is recommended to undertake repeated compass readings and average them, in order to increase 3D model precision.

3.4.1.2 Accuracy of measured discontinuity orientation

The results of this study are summarized in Fig. 3-6. It appears that approach C is consistently the most accurate. Table 3-3 compares the results obtained by the author with those obtained by Coggan et al. (2007) and Krosley et al. (2006). It is interesting to note in Fig. 3-6 that for all registration approaches the majority of the recorded dip residuals are less than 4°. Similarly, most of the observed dip direction residuals are less than 8°. As joints are never perfectly planar, a certain amount of scatter in orientation measurements is to be expected (Anon., 1977). Consequently, for this accuracy test, dip and dip direction values averaged from compass clinometer measurements are expected to be slightly different to values averaged from digital data measurements comprising a large number of points on a discontinuity surface. For this reason, it is suggested that
remote sensing estimation of discontinuity orientation is arguably more realistic than discrete compass clinometer measurements made at arbitrary locations. If joints are almost perfectly planar (such as discontinuities 4, 5 and 7 on the Mount Seymour rock cut) a maximum residual of $2^\circ$ and $6^\circ$ is observed for dip and dip direction, respectively, regardless of the registration approach used.

![Graphs showing mean errors and standard deviation of errors measured on 3D models registered using different approaches.](image)

**Figure 3-5.** Mean errors and standard deviation of errors measured on 3D models registered using the different approaches. (a) Mount Seymour, (b) Lake Louise, (c) Saskatchewan Crossing. TLS = terrestrial laser scanning, DP = digital photogrammetry. Capital letters refer to the corresponding registration approaches.
Based on discontinuity measurements in this study using all the registration approaches, the dip and dip direction residuals of 4° and 8°, respectively are chosen to represent approximate limits within which the site variability in discontinuity orientation measurements are constrained (Fig. 3-6). Larger residuals are observed and have a variety of origins; some resulting from the natural irregular surface profiles of discontinuities, e.g. discontinuity 5 on the Lake Louise rock cut is perpendicular to the schistosity, resulting in irregular surfaces. Discontinuity 2 measured at the Saskatchewan Crossing rock cut is an example of a surface covered with soil and rock debris, resulting in an apparent irregular discontinuity surface. Discontinuity 6 at the Saskatchewan Crossing rock cut is also irregular. Large residuals may also be observed on measurements taken along discontinuity traces (Mount Seymour, discontinuities 6 and 8; Lake Louise, discontinuity 3; Saskatchewan Crossing, discontinuity 4). Where joint traces are not sufficiently persistent and/or do not have adequate relief reliable orientation measurements on discontinuities may be difficult.

On the Lake Louise rock cut, dip direction residuals measured on TLS 3D models registered with approach A are systematically higher than 8°. Once again, it suggests that measured orientation accuracy is very sensitive to compass measurements and repeated readings are recommended when this registration approach set up is used.

Table 3-3. Discontinuity orientation accuracy using registration approach C.

<table>
<thead>
<tr>
<th>Discontinuity orientation accuracy</th>
<th>TLS</th>
<th>Digital photogrammetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dip residual</td>
<td>Dip direction residual</td>
</tr>
<tr>
<td>Mean [°]</td>
<td>Max. [°]</td>
<td>Mean [°]</td>
</tr>
<tr>
<td>Krosley et al. (2006)</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Coggan et al. (2007)</td>
<td>5.20</td>
<td>8.00</td>
</tr>
<tr>
<td>Present results</td>
<td>2.39</td>
<td>9.81</td>
</tr>
</tbody>
</table>
Figure 3-6. Discontinuity orientation accuracy estimated for each registration approach on selected discontinuities at the Mount Seymour, Lake Louise and Saskatchewan Crossing rock cuts. (a) Dip, (b) Dip direction.
3.4.1.3 Discussion of results

The foregoing analysis clearly highlights the superior accuracy and precision of approach C, using either CRTDP or TLS. If 3D models need to be registered with centimetre accuracy, this approach or to a lesser extent approach D, is recommended. However, for geotechnical purposes, it is often not necessary to achieve a high point accuracy and precision, because of the inherent natural spatial variability of rock mass discontinuity parameters. An important conclusion resulting from this study is that, even though some registration approaches provide relatively low absolute point accuracy (± 0.8 m) and relatively low precision (1.3 m), all provide adequate measurements of discontinuity dip and dip direction.

3.4.2 Ground resolution

In digital photogrammetry, ground pixel size depends on the focal length of the lens, the camera pixel size and the distance to the object. A number of ground pixels constitute the step size, which is the number of pixels used both horizontally and vertically to create one spatial point. The resultant ground resolution is called ground point spacing and is equal to the ground pixel size multiplied by the step size. For rock cuts it is normally recommended to use lenses with focal lengths between \( f = 20 \) and \( f = 50 \) mm. This allows capture of the entire rock cut using a practical number of photographs. Larger focal length can, in the case of rock cuts, result in an impractical and unnecessarily large number of photographs. However, when imaging large open pit or natural rock slopes at large object distances (1-2 km) it may be necessary to use lenses with \( f = 100 \) mm to \( f = 400 \) mm (Sturzenegger and Stead, 2009; Sturzenegger et al., 2009).

For laser scanning, Lichti and Jamtsho (2006) showed that angular resolution is function of both sampling interval and laser beamwidth. Consequently, they recommend that laser scanning angular resolution be expressed in terms of an EIFOV (Effective Instantaneous Field Of View), rather than the sampling interval alone. Table 3-4 shows the effective resolution that can be obtained with the ILRIS-3D for different scanner-rock cut distances. It is important to keep in mind that oblique scans or photographs will result
in lower resolution, so it is recommended to take sub-perpendicular scans or photographs wherever possible.

Table 3-4. Measures of resolution for the Optech ILRIS-3D (after Lichti and Jamtsho, 2006).

<table>
<thead>
<tr>
<th>Range [m]</th>
<th>Angular sampling interval [mm]</th>
<th>Laser beamwidth [mm]</th>
<th>EIFOV [mm]</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>0.13</td>
<td>12.85</td>
<td>11.0</td>
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<tr>
<td>20</td>
<td>0.52</td>
<td>15.4</td>
<td>13.2</td>
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<td>50</td>
<td>1.3</td>
<td>20.5</td>
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</tr>
<tr>
<td>100</td>
<td>2.6</td>
<td>29</td>
<td>25.0</td>
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<tr>
<td>200</td>
<td>5.2</td>
<td>46</td>
<td>39.8</td>
</tr>
<tr>
<td>500</td>
<td>13</td>
<td>97</td>
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</tr>
<tr>
<td>800</td>
<td>20.8</td>
<td>148</td>
<td>128.6</td>
</tr>
</tbody>
</table>

3.4.3 Occlusion

Numerous researchers have observed that, due to the phenomenon of occlusion, a complete rock face cannot be fully sampled from a single location. Occlusion occurs when parts of a rock face cannot be sampled because it is obscured by protruding features. It is important to minimize this effect by surveying the same outcrop from different positions, particularly where the outcrop displays significant changes in perspective. The varied data sets should be processed separately and/or merged into one single point cloud. Merging is achieved using the software IMAlign, part of the Polyworks package. A careful structural observation of rock cuts is recommended to minimize the potential for occlusion. Sturzenegger et al. (2007) emphasize that this occlusion phenomenon will not only occur horizontally, but also vertically (Fig. 3-7). A direct consequence of occlusion is orientation bias, which will be discussed further in Section 3.5.2.3.
Figure 3-7. Illustration of occlusion and vertical orientation bias (after Sturzenegger et al., 2007). (a) When the vertical line-of-sight of the camera/scanner is parallel to a discontinuity, there is potential for orientation bias. When the vertical line-of-sight of the camera/scanner is directed upwards at an angle steeper than a discontinuity, occlusion results in a shadow zone. (b) Rock cut view from the camera/scanner perspective, showing discontinuity traces.

3.5 Discontinuity mapping on 3D digital models

Discontinuity characterization is achieved by manually fitting planes on individual recognizable surfaces or traces in 3D models, using the software Polyworks and 3DM Analyst (Fig. 3-8). In both software codes it is assumed that the discontinuities are circular. Dip and dip direction are derived from the direction cosines of the normals to the planes. Discontinuity persistence is measured as the areal extent of each discontinuity (ISRM, 1978). In order to compare persistence values measured from 3D models with common trace length values, we will define the diameter of a circular discontinuity as an “equivalent trace length”. Both orientation and persistence measurements are then plotted on stereonets (Dips, Rocscience Inc., 2003) and histograms. The author emphasize that discontinuity mapping from remote sensing imagery (just as is the case for field
mapping) requires the appropriate geological expertise and skilled interpretation by a rock mechanics engineer or geoscientist. As for traditional discontinuity mapping, specific biases and limitations must be considered when using discontinuity data derived from laser scanning or digital photogrammetry.

Figure 3-8. Discontinuity characterization on 3D models. (a) Laser scanner point cloud with a selected sampling window, (b) circles fitted to recognizable discontinuity surfaces and traces.
3.5.1 Observation scale

A comparison of discontinuity surveys undertaken on two rock cuts, using traditional field scanlines and “virtual” scanlines on 3D digital models, is presented in Fig. 3-9. The comparison is based on measurements achieved along the same section of rock, at the base of the rock cut. It clearly shows that the traditional field scanlines provide significantly more data, the number of measurements along virtual scanlines being limited by the resolution of the 3D model (see Section 3.5.2.4 about truncation).

This example is not meant to imply that any of the methods is incorrect; rather that the observation scale is different and must be allowed for in the design of a remote sensing survey. Consequently, remote sensing surveys will have to cover a larger outcrop surface to provide statistically significant datasets. It is also possible to use a higher resolution, however, there are two limitations. First, as discussed in Section 3.4.2, resolution is practically or physically limited. In addition, one main advantage of the use of remote sensing techniques for rockcut characterization is to provide a comprehensive dataset, which is not limited to the toe of the rock slope, but covers most of its extent. It is recommended to use window mapping in order to fully optimize the advantages of terrestrial remote sensing techniques in sampling the higher elevation sections of a rock cut. Based on these preliminary observations, this chapter provides an evaluation of remote sensing techniques using sampling windows that cover the entire rock cuts (Fig. 3-8a).

3.5.2 Discontinuity characteristics

3.5.2.1 Discontinuity sets

Continuing previous work by Monte (2004), the reliability of remote sensing techniques for mapping the fracture pattern in various rock masses is assessed by comparing stereonets with discontinuity orientations to samples obtained using a conventional field scanline (Fig. 3-10). Stereonets obtained using a field scanline, from TLS and CRTDP agree closely, especially in the case of systematically oriented discontinuities (Figs. 3-10 g, h, i). Where the orientation of the discontinuity sets show a significant amount of scatter (Figs. 3-10 a, b, c and d, e, f), it is more difficult to assess
the quality of the 3D models, because the discontinuities compared along field scanlines and on virtual windows are not the same. Given that remote sensing surveys cover the entire rock cut, they provide more comprehensive datasets than field scanlines that are undertaken at the slope toe.

![Figure 3-9. Comparison between scanline surveys on rock cuts and remote sensing surveys along virtual scanlines (stereonets lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area). (a), (b), (c) Quartz Diorite, (d), (e), (f) Slate. Laser scanning: 7 mm < spot spacing < 15 mm, digital photogrammetry: f = 50 mm.](image)

This advantage is particularly important in the case of irregularly jointed rock masses, where discontinuity parameters measured along a scanline at the toe do not necessarily reflect the characteristics of discontinuities located higher on the rock cut.

The first step in a stability analysis commonly focuses on a kinematic analysis, which is based on the mean orientations of the discontinuity sets. All measured discontinuities are plotted on a stereonet, classified into sets and the mean orientation and persistence used for further analysis. The limestone rock cut at the Saskatchewan
Crossing rock cut (Fig. 3-3d and Figs. 3-10g, h, i) shows an example of a regular fracture network, which is well suited for such an analysis. However, other rock masses may not display such an organized network. Figures 3-3a and 3-11a show an example of a rock mass, where preferred discontinuity orientations are less obvious. Indeed, the rock cut shows a fairly irregularly jointed rock mass, possibly due to large variability in the sets present and/or curvature of the discontinuities. In this case, sampling discontinuities along a scanline at the toe of the rock cut and then extrapolating the results to other parts of the exposure would not be representative of the entire outcrop. In addition, specific hazardous discontinuities located higher on the cut may not be sampled. In contrast, terrestrial remote sensing techniques provide measurements of individual discontinuity orientations over an entire rock cut improving joint set definition and allowing the engineer to focus stability analysis on specific hazardous discontinuities located anywhere on the rock cut (Figs. 3-11a and b). This may have important implications both in rockfall hazard rating and in the design of rock slope remedial measures.

### 3.5.2.2 Discontinuity location

Terrestrial remote sensing techniques allow measuring the location in x,y,z or real world coordinates of individual discontinuities. In practice, it is important to consider the discontinuity location on the rock slope face in conjunction with its orientation in order to examine the spatial distribution of critical discontinuities susceptible to sliding or toppling failure. Figure 3-11c displays only those discontinuities included within the toppling envelope (Fig. 3-11a) and shows that the majority of potential toppling failure is liable to occur in the lower right section of the Seymour rock cut.
Figure 3-10. Comparison between pole and contour plots obtained from scanline, laser scanning and digital photogrammetry surveys (stereonets lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area). (a), (b), (c) Slate, (d), (e), (f) Quartz Diorite, (g), (h), (i) Bedded Limestone. Laser scanning: 7 mm < spot spacing < 15 mm, digital photogrammetry: $f = 50$ mm.
Figure 3-11. Kinematic analysis. (a) Potential planar failure along medium to very high persistence discontinuities at the Murrin Lake rock cut, (b) potential toppling failure at the Mount Seymour rock cut, (c) stereomodel of the Mount Seymour rock cut showing only the discontinuities susceptible to toppling.
3.5.2.3 Discontinuity orientation

Depending on its waviness, a discontinuity can be planar, undulating or even stepped (ISRM, 1978). A possible source of error, when measuring the orientation of an undulating/irregular discontinuity with a compass clinometer is related to where the mean discontinuity plane lies (Ross-Brown et al. 1973). Indeed, the size of the compass may be small relatively to the waviness wavelength. Terrestrial remote sensing techniques offer the possibility to measure orientation on a much larger surface providing more meaningful estimation of discontinuity mean orientation.

It is well established that discontinuity measurements obtained from conventional scanlines can be affected by orientation bias (Terzaghi, 1965). Orientation bias should be more limited using 3D models, because they allow discontinuity recognition and measurements on both surfaces and traces. However, the results presented in Section 3.4.1.2 highlight potential inaccuracies when measuring joint traces. Consequently, the author recommend special care when dealing with surfaces (discontinuities) that are sub-parallel to the camera/scanner line of sight, particularly where those discontinuities are daylighting (Fig. 3-7). Following a similar approach as adopted in conventional discontinuity mapping (Priest, 1993), laser scanning surveys should ideally be undertaken on rock slope faces of varying orientation and/or from varying scanner locations and elevations.

3.5.2.4 Discontinuity persistence

Persistence remains one of the most difficult rock mass parameters to quantify (ISRM, 1978), due to sampling bias including truncation, censoring, length bias and f-bias. During a traditional joint survey, truncation bias occurs where small traces are difficult or sometimes impossible to recognize/measure. Therefore, traces smaller than a defined cut-off length are not recorded (Zhang and Einstein, 1998). This problem is similarly encountered in the use of remote sensing techniques with truncation occurring where discontinuity surfaces smaller than a certain size are not visible or cannot be measured. In order to accurately recognize and measure a discontinuity surface, its dimensions must be significantly greater than the image resolution (Sturzenegger et al., 2007). Figure 3-12 shows the result of an evaluation of the persistence cut-off for field
scanline, TLS and CRTDP measurements. The cut-off value for remote sensing measurement is located between 0.2 and 0.6 metres. Features smaller than this value tend to be truncated, because they are either not visible or impractical to measure. Truncation resulting from remote sensing mapping may not be a significant limitation. On the contrary, it might be argued that these techniques provide an objective truncation system (with appropriate engineering judgment), automatically filtering discontinuities too small to play an important role in the kinematics of rock cut failure. When assessing block size and rock mass quality this limitation must, however, be considered with respect to image resolution.

In conventional mapping, censoring occurs when long discontinuity traces extend beyond the visible exposure, so that one or both ends cannot be seen (Zhang and Einstein 1998) leading to an underestimation of discontinuity size. In remote sensing surveys, censoring will occur both on the edge of the sampling windows and along discontinuity surfaces, where only one part of the surface is included in the sample (Fig. 3-13a).

Sturzenegger et al. (2007) highlight that censoring can also occur due to only a small part of a discontinuity surface being visible on a rock face; the major part being hidden within the rock mass or eroded (Fig. 3-13b). In scanline surveys, this bias is referred to by Priest (2004) as f-bias. It occurs, because the trace representing the intersection of circular discontinuities and a rock face will be chords produced by random sections across the circular discs.
Figure 3.12. Evaluation of the persistence cut-off value for remote sensing measurements, in both a Quartz Diorite and a Meta-Sedimentary rock. (a) Trace length distribution obtained with a scanline discontinuity survey, (b) equivalent trace length distribution obtained with a laser scanner discontinuity survey, (c) equivalent trace length distribution obtained with a digital photogrammetry discontinuity survey.
Figure 3-13. Schematic representation of a rock cut. The hatched area is the point cloud for the visible section of a discontinuity on a 3D model. Its true size is the shaded ellipsoid (after Sturzenegger et al., 2007). (a) Parts of the ellipsoid are censored, because they are either hidden in the outcrop or eroded, (b) the hatched area can represent any random area within the ellipsoid (f-bias).

During traditional field investigations, reliable estimation of discontinuity persistence is limited to 5 to 10 metres, and it is common to note the persistence as “5+ m” or “10+ m”, which represents a major and non-conservative simplification where major persistent structures may daylight in high rock cuts and large open pit mine slopes. Figure 3-12 shows how terrestrial remote sensing techniques are able to provide a much more accurate estimation of persistence. Indeed, while the trace length distributions obtained with a scanline become irregular above 1.5 to 2 metres (Fig. 3-12a), distributions obtained from TLS and CRTDP measurements appear more continuous and realistic (Figs. 3-12b and c). In other words, terrestrial remote sensing techniques allow more accurate quantification of medium to high persistence discontinuities (3 to >20
metres). The author suggest that current persistence classifications which consider persistence only up to lengths of greater than 20-30 m may require modification in light of developments in remote sensing data collection techniques capable of accurately quantifying critical and extremely high persistence discontinuities of particular importance in the stability of large open pits (1 km deep) and high rock cuts.

### 3.5.2.5 Discontinuity roughness and curvature

The use of analytical photogrammetry to quantify discontinuity roughness has been reported frequently in the literature (ISRM, 1978; Wickens and Barton, 1971) utilizing the coordinates of numerous points on a surface. If the direction of potential sliding is known, it is recommended to derive a profile along that direction (ISRM, 1978). Discontinuity roughness has recently been investigated by Fardin et al. (2004), Haneberg (2007) and Poropat (2008), using both TLS and CRTDP. These newly developed techniques greatly reduce the time required to measure point coordinates. The primary roughness and curvature are particularly amenable to investigation, because of the resolution of the 3D models. Curvature has been defined by Priest (1993) as “surface irregularities with a wavelength greater than about 100 mm”. It can be determined by measuring offsets at 100 mm intervals along a straight base line, then digitizing and quantifying the resulting profile.

Figure 3-14 shows two methods using 3D models to describe and quantify roughness or curvature. In Method 1 (areal morphology), all the spatial points belonging to a specific discontinuity surface are selected and an average plane is fitted. It is the equivalent in 3D of the linear profiling method described in the ISRM (1978). The roughness or curvature may then be characterized using an error map displaying the orthogonal distance between the average plane and the topography (Figs. 3-14a and 3-15). In Method 2 (“virtual” compass and disc-clinometer), orientation measurements are achieved at numerous places on a discontinuity by selecting points in windows of progressively increasing size (Fig. 3-14b). The average orientation of each of these windows is then plotted on stereonets, as shown on Fig. 3-16. This method is an adaption for digital photogrammetry/LiDAR point clouds of the compass and disc-clinometer method described in ISRM (1978).
Figure 3-14. Measurement of roughness or curvature. (a) Method 1: calculation of the orthogonal distance between an average plane and the topography, (b) Method 2: selection windows with progressively increasing size to measure orientation at numerous locations on the discontinuity surface.

An example of the description and quantification of the curvature of three persistent discontinuities on the Murrin Lake and Mount Seymour rock cuts is shown in Figs. 3-15 and 3-16. Figures 3-15a, 3-15c and 3-15e show linear profiles across the discontinuity surfaces. Figures 3-15b, 3-15d and 3-15f characterize curvature using Method 1. Finally, Fig. 3-16 quantifies curvature using Method 2. It is interesting to note that the two very high persistence discontinuities observed at the Murrin Lake rock cut are highly curved, with amplitude irregularities greater than 1.5 metres. In contrast, the amplitude along the medium persistence discontinuity at the Mount Seymour rock cut is one order of magnitude smaller.
Figure 3-15. Discontinuity curvature. (a) to (d), Very high persistence discontinuities at the Murrin Lake rock cut, (e) and (f) medium persistence discontinuity at the Mount Seymour rock cut. (a), (c), (e) show linear profiles along the discontinuities. (b), (d), (f) show areal quantification of curvature using method 1.
Figure 3-16. Discontinuity curvature quantified with method 2. (a) Murrin Lake, plane 1, (b) Murrin Lake, plane 2, (c) Mount Seymour, plane 1. For each selection window size, cones representing 99% variability have been plotted: thick line = 10 x 10, dashed line = 20 x 20, thin line = 40 x 40 and dotted line = 80 x 80 cm (stereonets lower hemisphere, equal area projection).
3.5.2.6 Additional discontinuity properties

Measurement of small discontinuity aperture may often be inherently unreliable, due to disturbance by blasting or surface weathering (ISRM, 1978). Remote sensing provides a useful method of characterizing the effects of blasting and weathering on rock slopes and variations on discontinuity aperture. Discontinuity aperture may be susceptible to large variations due to discontinuity surface roughness, particularly if there has been displacement by previous shearing. Depending on the size of the aperture, infill of various forms can separate the adjacent discontinuities rock walls. Unless the aperture is particularly wide, the resolution of conventional 3D models will be of limited use in infill characterization, however, some scope may exist for the measurement of infill width if an appropriate resolution is selected. Infill composition and width may significantly affect discontinuity strength and it is suggested that these characteristics are best observed directly on the outcrop during conventional field survey. More details concerning aperture and infill measurement/classification can be found in ISRM (1978), Priest (1993) and Ortega et al. (2006). Seepage from individual unfilled and filled discontinuities or from specific sets exposed in a surface are commonly assessed according to a seepage rating system (ISRM, 1978). Considerable potential exists for the use of 3D remote sensing models to visually estimate the presence and origin of seepage on rock cuts (Sturzenegger et al., 2007).

3.5.3 Limitations due to rock mass texture

Discontinuity characterization on 3D models may become a challenging task, depending on the rock mass texture. Field investigations in various rock masses has revealed that the use of remote sensing techniques is limited in certain rock masses that are in general characterized by a low Geological Strength Index (GSI) (Hoek and Brown, 1997; Hoek et al., 2002) and/or lack of rock slope surface relief.

During the current study, the author noted that remote sensing techniques were observed to be somewhat inefficient in two types of rock masses. The first is a very blocky monzonite outcrop (Fig. 3-17a), where the relief of the rock cut is low. Most of the visible discontinuities appear as traces, which results in measurement uncertainty particularly where discontinuity persistences are low (see Section 3.4.1.2). The second
case is a laminated siltstone, observed on the eastern side of the Manning Park rock cut (Fig. 3-17b). The resolution of remote sensing techniques in this case was insufficient to enable clear recognition/measurement of discontinuities.

Figure 3-17. Rock cuts with low relief (a) and low GSI (b). (a) Very blocky Monzonite, (b) Laminated Siltstone on the eastern section of the Manning Park rock cut.
3.6 Discussion and conclusion

This chapter evaluates the use of close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization and provides recommendations for optimizing the use of these techniques. The author emphasize the following.

i. Survey planning and 3D model quality are extremely important aspects in rock slope characterization using remote sensing techniques. This chapter has presented five 3D model registration approaches capable of providing accurate 3D models. A comparison of the discontinuity orientation data from this study with compass clinometer measurements indicates maximum residuals of 4° and 8° for dip and dip direction respectively. Such accuracy is suggested to be adequate for geotechnical purposes, due to the natural variability of discontinuity orientation. Higher residuals are suggested to reflect the fact that specific discontinuities are wavy or curved, and consequently, there is an inherent and unavoidable difference between compass clinometer and remote sensing measurements. Indeed, the former focus on a small area of a discontinuity, while the latter average a large number of points. It is suggested that remote sensing measurements may in fact provide a more realistic characterization of discontinuity orientation.

The results of this comprehensive study on varied rock types suggest that some registration approaches, which are easily and quickly set up and require limited access to a rock cut, are capable of providing adequate results for rock slope characterization. This is important in terms of time, effort and cost; considerable potential exists for rapid preliminary characterization of rock cuts using remote sensing techniques. It should be emphasized, however, that for important high risk applications, more accurate spatial measurements may be required and approaches incorporating adequate survey control are necessary. The author, based on the results of this research and the discussions at recent remote sensing workshops (Stead et al., 2007; Tonon and Kottenstette, 2007), emphasize the importance of developing guidelines for remote sensing of rock slopes. These would ensure standardized protocols for survey planning, data collection, and processing and aid in the selection
of the required quality of survey control for specific applications (Sturzenegger et al., 2007).

ii. A series of case studies in a variety of rock types have been presented to illustrate the application of remote sensing and possible limitations related to discontinuity characterization on 3D models. Occlusion and orientation bias have been emphasized as important phenomena that must be considered especially when daylighting discontinuities are present that dip parallel to the camera/scanner line-of-sight. The author recommend collecting as much information as possible on the geology and structure of a rock cut, allowing optimization of the location of the camera/scanner station prior to photography/scanning. 3D model resolution and truncation bias are also shown to limit discontinuity characterization in low GSI and low relief rock masses. In blocky rock masses, however, these limitations may in fact represent a significant advantage, as they are capable of systematically filtering non-persistent discontinuities and focusing observation on a more appropriate mapping scale.

It should be emphasized that this chapter illustrates the application of remote sensing for discontinuity characterization in rock cuts from relatively close ranges (about 30 to 160 m). An increasing number of terrestrial remote sensing projects, including large open pits and high mountainous slopes observations, are made at distances of 100’s to 1000’s of metres. Such projects require comprehensive consideration of rock slope observation scale (Sturzenegger and Stead, 2009; Sturzenegger et al., 2009).

iii. In addition to more realistic measurements of discontinuity orientation, terrestrial remote sensing techniques allow more accurate characterization of characteristics such as discontinuity location, persistence and curvature. They provide an opportunity to characterize discontinuities located in the upper part of rock cuts, resulting in a more comprehensive dataset. The location of individual discontinuities can be determined, related to their orientation, and subsequently incorporated into kinematic analysis. This process provides an evaluation of the distribution of discontinuities susceptible to planar or toppling failure over the entire rock cut. In addition, such deterministic approach does not require extrapolation of data measured along a scanline at the slope toe to the whole rock slope, in particular to the inaccessible and
often most prone to failure upper sections of the slope. Where the rock cut is composed of several domains varying with horizontal and vertical elevation, such extrapolations may lead to errors in rock slope stability assessment.

Discontinuity persistence can be measured more realistically, in particular when it exceeds 5 to 10 metres and exceeds common rock cut bench height values. In practice, field joint surveys often provide a rough estimation of such persistence, whereas remote sensing techniques, in contrast, allow the quantitative estimation of the actual lengths of critical joints. It is suggested that the existing ISRM classifications may reflect this upper truncation of persistence values and should be modified to include more realistic allowance for critical extremely persistence discontinuities; these discontinuities are the ones which may influence stability of high rock cuts and large open pit mines and should be given more emphasis in persistence classifications (the current ISRM persistence classification being biased to low persistence values). In addition, discontinuity waviness and curvature may also be quantified over the entire extent of the visible discontinuity surface and further work is suggested to extend current roughness classifications to this rock mass scale.

Parameters such as aperture, filling and small scale roughness are currently less amenable to remote measurement. Consequently, traditional and terrestrial remote sensing techniques are best used to complement each other.

iv. The author emphasize the benefits of the software available for visualization and analysis of 3D remote sensing rock slope models. These programs allow zooming, rotating and viewing point clouds from a variety of angles and enable a comprehensive observation and interpretation of rock cut data to allow improved visualization of the importance of discontinuities (Fig. 3-18).
Figure 3-18. 3D model of the Saskatchewan Crossing rock cut. (a) View from the side of the highway, (b) zoom in showing details of the fracture pattern, (c) plane view allowing better visualization of sub-vertical cross joints (dashed lines).
This chapter has emphasized both the progress and the bias associated with terrestrial remote sensing techniques, the objective being progress toward standardization in the use of remote sensing techniques for discontinuity characterization. The author recommend wherever possible the use of remote sensing derived 3D models in combination with high resolution photographs of the rock cut, and other available data sets. Geological observation and judgment, including the understanding of major structures and structural regions, should always remain the fundamental basis of any field investigation. In addition, the application of remote sensing techniques requires an understanding of principles of photogrammetry and the adoption of a strict methodology to ensure appropriate 3D model accuracy and resolution. The area to be mapped and physical constraints should be fully understood. Automated discontinuity measurements available in remote sensing software should be used with caution in order to avoid discontinuity measurement bias.

3.7 Acknowledgments

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3.8 Reference list


CHAPTER 4
QUANTIFYING DISCONTINUITY
ORIENTATION AND PERSISTENCE ON HIGH
MOUNTAIN ROCK SLOPES AND LARGE
LANDSLIDES USING TERRESTRIAL
REMOTE SENSING TECHNIQUES

The following chapter has been published as:

4.1 Abstract

This chapter describes experience gained in the application of terrestrial digital photogrammetry and terrestrial laser scanning for the characterization of the structure of high mountain rock slopes and large landslides. A methodology allowing the creation and registration of 3D models with limited access to high mountain rock slopes is developed and its accuracy verified. The importance of occlusion, ground resolution, scale and reflectivity are discussed. Special emphasis is given to the concept of observation scale and resulting scale bias and its influence on discontinuity characterization. The step-path geometry of persistent composite surfaces and its role in remote sensing measurements are described. An example of combined terrestrial digital photogrammetry and terrestrial laser scanning applied in the generation of a 3D model of the South Peak of Turtle Mountain, the location of the Frank Slide, is presented. The advantages gained from the combined use of these techniques and the potential offered through long-range terrestrial digital photogrammetry, using high focal length lenses up to 400 mm is illustrated. Special emphasis is given to the potential of this specific technique, which has to the author knowledge rarely been documented in the geotechnical literature.
4.2 Introduction

Terrestrial digital photogrammetry (TDP) and terrestrial laser scanning (TLS) are increasingly being recognized as efficient survey techniques for characterizing Earth surface morphology. McCaffrey et al. (2005) highlight the progress of digital geological fieldwork in terms of resolution, accuracy, data visualization, management and reproducibility. The combination of both airborne and terrestrial methods allows coverage of a wide range of observation scales and the ability to acquire data remotely; this makes it possible to overcome issues related to both accessibility and true representation of features. Applications in geosciences and geotechnics have been proposed by several authors. Rosser et al. (2005) highlight the benefits of topographic information provided by TLS surveys compared to the plan view provided by traditional airborne survey. They emphasize the importance of such techniques in quantifying the spatial distribution and magnitude of rockfall events associated with coastal cliff erosion. Pesci et al. (2007a, 2007b) demonstrate the suitability of laser scanning for monitoring both rapid morphological variations and physical changes of volcanoes and also integrate TLS and airborne digital photogrammetry to model an entire volcano. Nagihara et al. (2004) applied TLS to characterize the morphology of sand dunes. Teza et al. (2007, 2008) and Monserrat and Crosetto (2007) detail methodologies to measure landslide displacements and strain fields, based on the large amount of dense and accurate spatial information provided by terrestrial remote sensing techniques. Bellian et al. (2005) used TLS for stratigraphic modeling and Enge et al. (2007) to build petroleum reservoir models. Abellan et al. (2006) integrate TLS in the process of rock fall hazard assessment, emphasizing the collection of more accurate information on joint geometry, block volume and location, and rock fall trajectory. Pötsch et al. (2006) show how discontinuity data measured on highwalls using TDP can be integrated into kinematic analysis. Finally, Tannant et al. (2006) recognize the potential of TDP for surveys in open-pit mine environment.

Close range applications of terrestrial remote sensing techniques including discontinuity characterization on rock cuts has been documented by the present author (Sturzenegger and Stead, 2009) and numerous other workers (Ferrero et al., 2009; Slob et
al., 2005; Monte, 2004; Kemeny et al., 2006; Jaboyedoff et al., 2008; Haneberg, 2007 and 2008; Gaich et al., 2006; Feng and Röshoff, 2004; Coggan et al., 2007; Birch, 2006; Poropat, 2006 and 2008; Lato et al., 2009). The extension of such characterization to a longer range requires an investigation of the influence of scale effects. The present chapter will initially focus on high mountain rock slopes in general and then describe in detail a large landslide surveyed from distances between one hundred metres and more than two kilometres. When characterizing rock mass discontinuities at such distances, questions regarding the accuracy, ground resolution and survey network building will arise. In addition, it will be important to understand which type of features can be mapped and what will be the effect of the observation scale on their measurements. Particular emphasis will be given to this concept, also termed “scale bias” by Ortega et al. (2005).

After a brief description of the field methodology, some specific considerations about network setting, ground resolution, scale, accuracy and precision will be discussed. A detailed study concerning discontinuity orientation and persistence characterization using terrestrial remote sensing 3D models at scales up to 1:11000 is followed by application to the South Peak of Turtle Mountain, location of the 1903 Frank Slide. The latter investigation demonstrates the benefits of combining TDP and TLS and highlights the potential of long-range TDP using high focal length lenses (up to 400 mm).

4.3 Field methodology

Characterization of high mountain rock slopes is often constrained by accessibility and safety issues. Consequently, terrestrial remote-sensing techniques represent promising alternatives/supplements to traditional rock engineering scanline or window mapping methods. The laser scanner used in this project is an Optech ILRIS-3D (Optech Inc., 2008) with data processing undertaken using the commercial code Polyworks (InnovMetric software, 2006). Digital photogrammetry data imagery is obtained using a Canon EOS 30D digital camera with varying focal length lenses and processed using the 3DM Calibcam/Analyst software (Adam Technology, 2007).
An important component of terrestrial remote-sensing surveys is the registration of 3D models. Depending on the purpose of the work, the user may wish to survey control targets on the rock slope itself and this operation can quickly become the most time-consuming component of a project. Four alternative approaches using a differential GPS (DGPS), a reflectorless Total Station (TS) and/or a compass are proposed and compared (Table 4-1 and Fig. 4-1). Some of these approaches do not require access to the rock slope. Note that for the particular application of rock slope characterization, registration into the global reference system is not always necessary; all that is required being to orientate a 3D model relative to north in a local reference system.

Table 4-1. Registration approaches.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Compass measurement of the trend and plunge of the camera/scanner line-of-sight. Using TDP, the scale is provided by measurement of the distance between the two camera positions. The tilt must be zeroed. No access to the rock slope is required. The point precision and accuracy of this approach has not been tested over a distance larger than 300 m. However, a comparison of the orientation of four selected planes measured using approaches A, B and C shows consistent results (Table 4-4 and Fig. 4-4).</td>
</tr>
<tr>
<td>B</td>
<td>Three or more photographs/scans are taken from three different positions and merged together; these positions are surveyed with the TS. No access to the rock slope is required. The point accuracy of this approach is lower than approach C-1 and C-2 as, since there is no control point in the neighbourhood of the rock slope, a small inaccuracy in the survey of the camera/scanner positions will propagate with the distance. However, measurements of discontinuity orientation are still valuable as shown in Table 4-4 and Fig. 4-4.</td>
</tr>
<tr>
<td>C-1</td>
<td>Survey of about 6 targets on the rock slope, using a DGPS or TS. The position(s) of the camera/scanner can be incorporated, if available. This approach is the most accurate and precise.</td>
</tr>
<tr>
<td>C-2</td>
<td>Survey using the reflectorless TS of about 6 natural recognizable and scattered features on the rock face. The position(s) of the camera/scanner can be incorporated, if available. No access to the rock slope is required.</td>
</tr>
</tbody>
</table>
Figure 4-1. Registration approach set-up. The squares represent camera/scanner positions and the stars control points. The filled symbols or lines indicate measurement locations.

The registration devices used in this project are a single frequency Thales Promark3 DGPS (Thales Group, 2008) and a Topcon GPT-3002LW long-range reflectorless total station (Topcon Positioning System Inc, 2008). The DGPS and TS precision are a few centimetres and a few millimetres, respectively. If used in reflectorless mode on natural features in a rock slope located a few hundreds metres away, the expected precision of the TS is in the order of a few centimetres (Lim et al., 2005) and its maximum range under optimal conditions is 1200 metres (Topcon Positioning system Inc., 2008).

Fieldwork has been performed at four locations in the Canadian Rocky Mountains (Table 4-2 and Fig. 4-2).
Table 4-2. Rock slopes investigated.

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Rock type</th>
<th>Age</th>
<th>Structure</th>
<th>Images area: height/length</th>
<th>Average slope dip/dip direction</th>
<th>Average range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turtle Mountain (Fig. 4-2a)</td>
<td>Highway 3, near Frank, Alberta</td>
<td>Livingstone Formation (Douglas, 1958). Thick beds of medium- to coarsely-crystalline limestone</td>
<td>Lower Carboniferous</td>
<td>Gentle slope with highly fractured rock, close to the hinge of an anticline; presence of tension cracks</td>
<td>80/100</td>
<td>42/111</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and medium-crystalline, porous dolomite which alternate as individual beds or in larger units with</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>beds of finely crystalline limestone, argillaceous, dolomitic or cherty, and fine-grained dolomite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mount Edith Cavell (Fig. 4-2b)</td>
<td>20 km south of Jasper, Alberta</td>
<td>Gog Group (Aitken, 1968). Thick units of very fine and fine-grained sandstone and quartzite.</td>
<td>Lower Cambrian</td>
<td>Very brittle and intensively fractured rock; anacinal slope</td>
<td>160/240</td>
<td>72/053</td>
<td>550</td>
</tr>
<tr>
<td>Bridal Veil Falls (Fig. 4-2c)</td>
<td>Highway 93, between Saskatchewan Crossing and Jasper, Alberta</td>
<td>Palliser Formation (Beach, 1943; Meijer Drees et al., 1993). Lower (Morro) Member: massive and resistant, cliff forming, grey and dark greyish brown mottled, dolomitic limestone. Upper (Costigan) Member: interbedded succession of dolostone, silty dolostone and fossiliferous limestone.</td>
<td>Upper Devonian</td>
<td>Steep anacinal rock slope, with overhanging blocks</td>
<td>65/145</td>
<td>87/191</td>
<td>430</td>
</tr>
<tr>
<td>Medicine Lake (Fig. 4-2d)</td>
<td>20 km east of Jasper, Alberta</td>
<td></td>
<td></td>
<td>Structure dominated by bedding planes, subparallel to the rock slope face; 2 or 3 sets of cross joints form lateral and upper release</td>
<td>7/15</td>
<td>55/226</td>
<td>23</td>
</tr>
</tbody>
</table>
Figure 4-2. Field localities. a) Turtle Mountain, b) Mount Edith Cavell, c) Bridal Veil Falls, d) Medicine Lake, e) map of western Canada with the field locations.

4.4 Survey planning, data acquisition and processing

This section briefly reviews the main parameters to consider when planning a TDP or TLS survey. Additional general considerations for the application of terrestrial remote sensing techniques to geological investigations can be found in Buckley et al. (2008).
4.4.1 Network setting

Ideally, the position(s) of the camera/scanner should be chosen to attain the expected resolution and accuracy, and to minimize the potential for occlusion and orientation bias with respect to both horizontal and vertical fields of view (Sturzenegger et al., 2007a). Consequently, a preliminary geological and structural geology survey of the rock slope should always be attempted. Topographic constraints in the field often limit the degree of flexibility in setting up a survey network. In particular, most of the rock slopes investigated can only be surveyed from below, access being limited to the foot of the mountain slopes.

4.4.2 Ground resolution

Spatial resolution in both photographic and non-photographic remote sensing requires the use of the concept of a ground resolution cell (GRC), representing the size of a scene element, i.e., the dimensions on the ground of the basic element of the image (Rengers et al., 1992; Strandberg, 1967). For terrestrial remote-sensing techniques, this is the ground point spacing. For digital photogrammetry, ground point spacing depends on the step size, which quantifies the number of pixels used, both horizontally and vertically, to generate a spatial point. The ground pixel size should be multiplied by the step size to obtain the ground point spacing.

Ground resolution is not a constant value, particularly on tilted aerial or terrestrial images. Several parameters, including incidence angle, reflectivity, stereomatching and changes in perspective all may influence ground resolution. As a general rule, use of a slightly higher resolution (i.e., a slightly shorter ground point spacing) is recommended, so that there is enough redundancy to guarantee adequate interpolation of a 3D model surface (Giussani and Scaioni, 2004).

In digital photogrammetry, resolution is a function of the focal length, pixel size and the range, whereas for laser scanning, resolution depends on both beamwidth, which defines the footprint, and spot spacing. Lichti and Jamtsho (2006) combine these parameters in a measure called effective instantaneous field of view (EIFOV). The footprint represents the size of the area averaged in a single laser beam measurement and
can be calculated using equations proposed by Giussani and Scaioni (2004). Excessively oblique scans, horizontally or vertically, should be avoided. Indeed, Pesci et al. (2007a) show that if the angle between the beam line-of-sight and the normal to the object surface is greater than 60°, the footprint decreases dramatically with increasing range. A similar logic can be used for digital photogrammetry surveys.

McCaffrey et al. (2005) state that fine (cm) scale resolution allows the user to map stratigraphical contacts, meso-scale tectonic and sedimentary structures, or weathering and other surface processes. Terrestrial remote sensing techniques allow the characterization of sub-vertical slopes at a fine (cm) to very fine (mm) resolution. Such level of detail makes it possible to measure low to extremely high persistence discontinuities (ISRM, 1978; Sturzenegger and Stead, 2009). Terrestrial reflectorless surveying methods are best used on sub-vertical sections, while airborne techniques are superior for sub-horizontal landscapes.

### 4.4.3 Scale

On aerial and tilted photographs, in variable relief terrain, the scale can be measured at a specific location, but only approximated as an average scale over an entire area. For more details on scale calculation, refer to Wolf and Dewitt (2000). Equation 4-1 can be used to approximate terrestrial photographic scale (note that the scale does not change when zooming in or out, although it may help visually):

$$ S_{avg} = \frac{f}{D} $$

(4-1)

where $f$ is the focal length and $D$ the range. For example, outcrop scale is 1:600 with a 50 mm focal length at 30 metres while the scale for a high mountain rock slope, at 500 m with $f = 200$ mm, is 1:2500.

A certain number of pixels are needed to recognize a feature in an image; the actual minimum number of pixels required varying according to the contrast between the feature and its background. If there is sufficient contrast, Soeters and van Westen (1996) suggest that on 1:50000 (medium scale) aerial photos, the minimum size of a recognizable object is 25 m², and increasing to 6.5 m² at a larger scale of 1:15000. In
addition, Sissakian et al. (1983) estimated that slope instability features, such as cracks, steps and depressions, should be 10 to 75 metres long to be adequately recognized at 1:5000 scale and larger than 75 metres to be identified at 1:10000 scale.

4.4.4 Precision and accuracy

In digital photogrammetry, the precision and accuracy of a stereomodel depend mainly on the network geometry (Fraser, 1996; Adam Technology, 2007), i.e., the relative positions of the camera and the object. In laser scanning, each manufacturer provides precision and accuracy specifications, which have been verified by Boehler et al. (2003) and Pesci et al. (2007a). Precision and accuracy will largely depend on registration of a 3D model into a local or global reference system. Whenever possible, it is recommended to measure a few reference points in the neighbourhood of the rock slope in order to evaluate precision and accuracy.

Using the TS survey as the base case, the author tested the accuracy (mean error) and precision (standard deviation) of varying techniques and registration approaches (see Lane et al., 2000) at Bridal Veil Falls and Turtle Mountain (Table 4-3 and Fig. 4-3), with a range of 430 m and 2100 m, respectively. Note that no correction for Earth curvature and refraction has been applied, because their effect would be insignificant at the present range (Topcon Positioning system Inc., 2008). The results show that approach C-1 and C-2 are the most accurate and precise with an average mean error of 0.1, 0.05 and -0.03 m and an average standard deviation of 0.28, 0.15 and 0.17 m in the X-, Y- and Z-directions, respectively. The point accuracy and precision of approach B is significantly lower, with an average mean error of 2.91, 7.00 and 0.02 m. and an average standard deviation of 0.47, 0.49 and 0.74 m in the X-, Y- and Z-directions, respectively.
Table 4.3. Accuracy (ME = mean error) and precision (SD = standard deviation) of the registration approaches used at Bridal Veil Falls and Turtle Mountain (TDP using varied focal lengths).

<table>
<thead>
<tr>
<th>Technique/f</th>
<th>Registration approach</th>
<th>Range [m]</th>
<th>X me [m]</th>
<th>Y me [m]</th>
<th>Z me [m]</th>
<th>X sd [m]</th>
<th>Y sd [m]</th>
<th>Z sd [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDP 100 mm</td>
<td>B</td>
<td>430</td>
<td>1.49</td>
<td>4.81</td>
<td>5.59</td>
<td>0.43</td>
<td>0.36</td>
<td>0.99</td>
</tr>
<tr>
<td>TDP 200 mm</td>
<td>B</td>
<td>430</td>
<td>-1.12</td>
<td>2.95</td>
<td>0.64</td>
<td>0.18</td>
<td>0.74</td>
<td>0.92</td>
</tr>
<tr>
<td>TLS</td>
<td>C-2</td>
<td>430</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.07</td>
<td>0.18</td>
<td>0.08</td>
</tr>
<tr>
<td>TDP 50 mm</td>
<td>C-2</td>
<td>430</td>
<td>0.06</td>
<td>0.00</td>
<td>-0.03</td>
<td>0.17</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>TDP 100 mm</td>
<td>C-2</td>
<td>430</td>
<td>-0.21</td>
<td>0.06</td>
<td>-0.30</td>
<td>0.38</td>
<td>0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>TDP 200 mm</td>
<td>C-2</td>
<td>430</td>
<td>-0.01</td>
<td>0.05</td>
<td>-0.02</td>
<td>0.31</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>TDP 400 mm</td>
<td>C-2</td>
<td>430</td>
<td>0.49</td>
<td>-0.16</td>
<td>0.30</td>
<td>0.25</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>TDP 400 mm</td>
<td>C-1</td>
<td>2100</td>
<td>8.37</td>
<td>13.22</td>
<td>-6.16</td>
<td>0.80</td>
<td>0.36</td>
<td>0.31</td>
</tr>
<tr>
<td>TDP 400 mm</td>
<td>C-1</td>
<td>2100</td>
<td>0.29</td>
<td>0.33</td>
<td>-0.13</td>
<td>0.47</td>
<td>0.09</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Figure 4.3. Accuracy (a) and precision (b) of the registration approaches used at Bridal Veil Falls and Turtle Mountain (TDP using varied focal lengths).

Table 4-4 and Fig. 4-4 show good consistency in the plane orientation measurements achieved using the different techniques and registration approaches. With the exception of the dip angle of plane D, all concentrations have very high Fisher’s K values, corresponding to maximum dip and dip direction variations with respect to the mean of 3.3° and 5.1°, respectively. The dip angle variability of plane D is relatively high, 5.2°, but still adequate for many engineering purposes. Note that planes B and C
could not be measured with TDP \((f = 400\, \text{mm})\), because they lie outside the sampling window. In addition, plane accuracy could not be evaluated at a range of 2100 m (on Turtle Mountain), because insufficient data were available.

Figure 4-4. Stereonet (lower hemisphere, equal area projection) of the measurements of planes A to D, made with the various techniques.

Table 4-4. Orientation of selected planes measured with the different techniques and registration approaches at Bridal Veil Falls, range = 430 m.

<table>
<thead>
<tr>
<th>Technique/f Registr. approach</th>
<th>Plane A</th>
<th>Plane B</th>
<th>Plane C</th>
<th>Plane D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dip(^\circ)</td>
<td>Dip direction(^\circ)</td>
<td>Dip(^\circ)</td>
<td>Dip direction(^\circ)</td>
</tr>
<tr>
<td>TLS A</td>
<td>23.8</td>
<td>38.8</td>
<td>86.1</td>
<td>69.4</td>
</tr>
<tr>
<td>TDP 50 mm B</td>
<td>24.6</td>
<td>38.0</td>
<td>84.1</td>
<td>68.3</td>
</tr>
<tr>
<td>TDP 100 mm B</td>
<td>25.7</td>
<td>31.9</td>
<td>84.1</td>
<td>73.3</td>
</tr>
<tr>
<td>TDP 200 mm B</td>
<td>23.4</td>
<td>37.3</td>
<td>83.9</td>
<td>69.2</td>
</tr>
<tr>
<td>TLS C-2</td>
<td>23.7</td>
<td>39.7</td>
<td>88.3</td>
<td>71.8</td>
</tr>
<tr>
<td>TDP 50 mm C-2</td>
<td>28.3</td>
<td>32.7</td>
<td>84.9</td>
<td>67.4</td>
</tr>
<tr>
<td>TDP 100 mm C-2</td>
<td>23.5</td>
<td>40.7</td>
<td>84.8</td>
<td>67.5</td>
</tr>
<tr>
<td>TDP 200 mm C-2</td>
<td>24.7</td>
<td>39.4</td>
<td>87.2</td>
<td>70.5</td>
</tr>
<tr>
<td>TDP 400 mm C-2</td>
<td>22.5</td>
<td>36.5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Mean orientation C-2</td>
<td>25</td>
<td>37</td>
<td>86</td>
<td>69</td>
</tr>
<tr>
<td>Fisher’s K</td>
<td>1322</td>
<td>896</td>
<td>3391</td>
<td>523</td>
</tr>
</tbody>
</table>
4.4.5 Reflectivity

Because laser scanners emit their own light, they have specific limitations related to object roughness and reflectivity (Optech Inc., 2008). Pesci et al. (2007a) achieved a successful laser scanner survey on low reflectance volcanic rocks at a range of 600 metres. Sturzenegger et al. (2007a) reported reflectivity issues on dark and wet rock masses at distances of 600 metres and 300 metres, respectively.

TLS tests at a coal mine, in south-eastern British Columbia, provided the limitation of the ILRIS-3D laser scanner on a typical low-reflectance rock mass. Results showed that, on coal, reflectivity issues can occur at a range of 350 metres and point cloud data are unreliable beyond 450 metres. On brighter rock masses, however, the range extends up to about 800 m.

4.5 Characterization of discontinuity orientation and persistence

The present work focuses on the characterization of discontinuity orientation and persistence. For details on roughness characterization using remote-sensing techniques, the reader should refer to Haneberg (2007), Poropat (2008) and Sturzenegger and Stead (2009). Research on quantification of spacing, intensity and block size is ongoing and outside the scope of the current chapter.

Field-based discontinuity characterization along scanlines (or windows) requires a large enough area to be mapped in order to obtain a statistically significant sample. In addition, it is recommended to map different exposures in order to avoid orientation bias (ISRM, 1978; Priest, 1993). The procedure is similar in 3D LiDAR and photogrammetric models where discontinuity orientation and persistence measurements are achieved by manually fitting planes on recognizable surfaces and traces using the commercial codes Polyworks (InnovMetric software, 2006) and 3DM Analyst (Adam Technology, 2007), respectively. Discontinuity characterization requires skilled interpretation by a rock mechanics engineer or geoscientist. Circular planes are assumed and discontinuity parameters including dip, dip direction and persistence are derived (Chapter 3: Sturzenegger and Stead, 2009) where the latter is calculated as the area of a circle whose diameter is termed the “equivalent trace length”.
Figure 4-5a illustrates this process on a detailed view from a point cloud of the Bridal Veil Falls rock slope. Each spatial point has a greyscale intensity value, which helps in distinguishing morphological features. Figure 4-5b shows the equivalent result on a stereomodel draped with a digital photograph. Large and/or multiple windows were used in order to ensure that enough measurements could be made and to avoid orientation bias. The white rectangles on Fig. 4-5 show the windows used at Bridal Veil Falls and the black rectangles on Fig. 4-6a the windows at Mount Cavell. Field measurements achieved on selected discontinuities at the foot of the Mount Cavell rock slope show that three orthogonal sets are present with a mean discontinuity trace length of 1.99 m (Fig. 4-6b). Close-range TDP, with a 20 mm focal length, was also undertaken at locations A and B (Fig. 4-6a).

4.5.1 Observation scale

At Bridal Veil Falls and Mount Edith Cavell, a series of 3D models with increasing ground resolution have been built. The ground resolution of the TLS point clouds is determined by varying the laser beam spot spacing value. Different focal lengths \( f = 20, 50, 200 \) and 400 mm) are used for the digital photogrammetric survey. The objective is to investigate the effect of observation scale on the results of the characterization of discontinuity orientation and persistence over constant sampling windows, by varying ground resolution. Preliminary results concerning the effect of the measurement scale on discontinuity roughness have been reported by Poropat (2008).
Figure 4-5. Discontinuity characterization on 3D models. (a) TLS point cloud, rendered with greyscale intensity values, b) photogrammetric stereomodel, draped with a digital photograph. The white rectangles indicate the sampling windows used with TLS, TDP 50 mm and TDP 200 mm. The white dashed line indicates the sampling window used with TDP 400 mm. The black squares illustrate how discontinuities are mapped through a detailed 3D view of the rock slope.
Figure 4-6. The Mount Cavell rock face. (a) Windows 1, 2 and 3 show where discontinuity characterization of 3D models was undertaken. “A” is the location of field measurements. “A” and “B” are the locations of close-range 20 mm TDP. (b) Discontinuity orientation and trace length measured by hand at station A.

4.5.1.1 Effect of observation scale on orientation measurements

Orientation measurements obtained for the different ground resolutions are shown in Figs. 4-7 and 4-8, at Bridal Veil Falls and Mount Edith Cavell, respectively. Figure 4-7 shows that high resolution 3D models clearly display the bedding, two sets of cross joints (J1 and J2) and an additional joint set (J3) (Figs. 4-7b and d). At a lower resolution, however, while the persistent bedding planes still clearly appear, J2 and J3 are poorly
defined (Figs. 4-7a and c). Consequently, there is a scale orientation bias resulting from the choice of resolution.

Figure 4-8 shows a fracture network with bedding planes and 2 sets of cross joints. Window 1 is located in a different domain from the other windows. Windows 1 and 2 display only two sets each; an additional window on a different exposure being necessary in order to compensate for orientation bias. Comparing the results obtained at varying resolutions for each window separately, very similar discontinuity sets can be recognized. However, a careful look at set J3 measured with TDP 50 mm in window 1 reveals a difference of 9 degrees in dip direction, compared to the average values obtained with the other resolutions. Similarly, there is a difference of 9 degrees in dip direction on set J1 in window 3. In addition, in window 1, the 400 mm digital photogrammetry model allows characterization of the non-persistent discontinuity set J2, which was not clearly recognized on lower resolution 3D models. These observations at Mount Edith Cavell confirm the possibility of additional orientation bias related to the observation scale, i.e., scale bias, when using low resolution 3D models. It shows that this observation scale effect can result in both a lack of measurements for a discontinuity set (Fig. 4-7) and a shift in discontinuity set orientation (Fig. 4-8).
Figure 4-7. Stereonets (lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area) of Bridal Veil Falls rock slope, obtained from 3D model discontinuity characterization. (a) TLS low resolution, b) TLS high resolution, c) TDP $f = 50$ mm lens, d) TDP $f = 200$ mm lens.
Figure 4-8. Discontinuity orientation measurements at Mount Edith Cavell (Stereonets, lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area). No measurements in windows 2 and 3 were done with TDP 400 mm.
4.5.1.2 Effect of observation scale on persistence measurements

Table 4-5 summarizes the results of persistence measurements obtained at Bridal Veil Falls and Mount Edith Cavell, highlighting differences in mean, minimum and maximum equivalent trace length. An effort was made to map the majority of recognizable and practically measurable discontinuities. As would be expected, the measured equivalent mean trace length increases with an increase in the ground point spacing; at each ground resolution, traces shorter than the minimum equivalent trace length being truncated. This truncation is the first effect of scale bias on discontinuity persistence measurements, i.e., non-recording of a certain persistence range.

3D model resolution can have a second scale bias effect on discontinuity persistence measurement in that discontinuities considered as extremely persistent when measured at low resolution may in fact be subdivided into a series of shorter discontinuities, this only being recognizable at higher resolution (Fig. 4-9). Such a step-path geometry is described in more detail in Section 4.5.2.

Table 4-5. Characterization of persistence.

<table>
<thead>
<tr>
<th>Location</th>
<th>Technique/f</th>
<th>Range [m]</th>
<th>Ground point spacing [m]</th>
<th>Mean eq. trace length [m]</th>
<th>Min. eq. trace length [m]</th>
<th>Max. eq. trace length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medicine Lake</td>
<td>TLS</td>
<td>23</td>
<td>0.013</td>
<td>2.24</td>
<td>0.30</td>
<td>17.40</td>
</tr>
<tr>
<td>Bridal Veil Falls</td>
<td>TDP 50 mm</td>
<td>430</td>
<td>0.442</td>
<td>11.83</td>
<td>2.00</td>
<td>45.00</td>
</tr>
<tr>
<td>Bridal Veil Falls</td>
<td>TDP 200 mm</td>
<td>430</td>
<td>0.110</td>
<td>5.76</td>
<td>0.50</td>
<td>44.00</td>
</tr>
<tr>
<td>Bridal Veil Falls</td>
<td>TDP 400 mm</td>
<td>430</td>
<td>0.055</td>
<td>3.97</td>
<td>0.39</td>
<td>52.44</td>
</tr>
<tr>
<td>Bridal Veil Falls</td>
<td>TLS</td>
<td>440</td>
<td>0.321</td>
<td>9.82</td>
<td>3.00</td>
<td>46.00</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TDP 20 mm</td>
<td>6</td>
<td>0.015</td>
<td>1.15</td>
<td>0.16</td>
<td>5.72</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TDP 50 mm</td>
<td>550</td>
<td>0.560</td>
<td>22.61</td>
<td>2.86</td>
<td>158.74</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TDP 200 mm</td>
<td>550</td>
<td>0.140</td>
<td>13.83</td>
<td>1.55</td>
<td>87.74</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TDP 400 mm</td>
<td>550</td>
<td>0.070</td>
<td>6.82</td>
<td>0.92</td>
<td>70.75</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TLS</td>
<td>550</td>
<td>0.180</td>
<td>8.58</td>
<td>1.60</td>
<td>56.01</td>
</tr>
<tr>
<td>Mt. Edith Cavell</td>
<td>TLS</td>
<td>550</td>
<td>0.090</td>
<td>5.05</td>
<td>1.00</td>
<td>44.01</td>
</tr>
</tbody>
</table>
Figure 4-9.Apparently persistent feature at low resolution (white line) comprising a step-path of low persistence steeper discontinuities (black lines).

For each 3D model, equivalent trace length measurements follow a negative exponential distribution. Results displayed in Table 4-5 are plotted in Fig. 4-10 and Fig. 4-10a shows the minimum equivalent trace lengths, which can be measured depending on both the ground resolution and scale. Figure 4-10b shows the mean equivalent trace lengths. Both graphs show that, based on the limited amount of available data, the trace length measurements fit approximately a linear trend line. Figure 4-10c shows that mean equivalent trace length measurements provide a better fit to power laws, when they are subdivided according to the rock type. Equations 4-2 and 4-3 are derived from the linear trend lines.

Ground point spacing = 0.145 * minimum equivalent trace length \hspace{1cm} (4-2)

Ground point spacing = 0.023 * mean equivalent trace length \hspace{1cm} (4-3)
Figure 4-10. Plots showing the relationship minimum (a) and mean trace length (b and c) versus ground point spacing and scale. Plot “c” shows that for both limestone and quartzite data a better fit is provided by a power law.
4.5.2 Step-path geometry

High resolution 3D models are particularly helpful in the observation of composite surfaces characterized by a step-path geometry. Characterization of step-path surfaces using TLS has been undertaken by Yan (2008). In this study, two main types of step-path geometries were observed. The first one, on Mount Edith Cavell (Figs. 4-9, 4-11a and b), shows a series of closely-spaced, sub-parallel, non-persistent discontinuities linked by an intact rock bridge. Once the intact rock bridge has failed, a persistent composite release surface or discontinuity surface may be created. This type of geometry has also been observed in the Palliser Formation limestone, on the Cirrus Wall, 5 km south of Bridal Veil Falls. A series of 10 m persistent, 1-2 m spacing, sub-horizontal bedding planes create the upper release surface of a large failure or series of failures (Fig. 4-12).

The second type of step-path geometry, observed in the Medicine Lake outcrop (Fig. 4-13), is characterized by a combination of two sub-perpendicular discontinuity sets and some intact rock bridges. As for the previous type, the entire discontinuity system provides the potential for persistent composite release surfaces. The example shown in Fig. 4-13 illustrates this with two sets of low persistence cross joints, sub-perpendicular to bedding and intact rock bridge length of up to 2 metres.

More complex step-path geometries, involving a larger amount of intact rock brittle fracture are described by Yan (2008).
Figure 4-11. First type of step-path geometry, observed on Mount Edith Cavell. A series of closely-spaced, sub-parallel, non-persistent discontinuities are linked by a narrow intact rock bridge. Discontinuity mapping on a TLS point cloud, rendered using greyscale intensity values.
Figure 4-12. The Cirrus Wall. (a) Photograph of the base of the wall, highlighting an upper release surface, (b) TLS point cloud, rendered using greyscale intensity values (white spots indicate no TLS measurement), showing characterization of the step-path geometry.
Figure 4-13. Second type of step-path geometry, observed at the Medicine Lake outcrop. The composite surface is composed of a combination of two sub-perpendicular discontinuity sets and some intact rock fractures. Discontinuity mapping on TLS point clouds, rendered using greyscale intensity values.
4.6 Composite terrestrial 3D model of the South Peak of Turtle Mountain

Turtle Mountain (Fig. 4-14a), the site of the 1903 Frank Slide, has been subject of numerous recent studies, as outlined by Froese and Moreno (2006). Conventional field-based mapping, using intrusive and non-intrusive methods have been applied (Cruden and Krahn 1973; Fossey 1986; Couture 1998; Spratt and Lamb 2005; Theune et al., 2005; Langenberg et al., 2006). Airborne remote-sensing techniques, including SAR and InSAR methods (Singhroy and Molch, 2004; Singhroy et al., 2005; Mei et al., 2008), photogrammetry (Jaboyedoff et al., 2009) and LiDAR (Sturzenegger et al., 2007b) have been used to monitor motion or characterize both the mountain and the morphology of the debris.

![South Peak](image)

**Figure 4-14.** Turtle Mountain. (a) East side with the limit of the slide (white dashed line), (b) contour map of the mountain with the locations of the TDP (black dots) and the TLS (black stars).

The structure and geology of Turtle Mountain has been described by Cruden and Krahn (1973) and further detailed by Langenberg et al. (2006). It is formed by the Turtle Mountain Anticline, which is underlain by the Turtle Mountain thrust fault. Above this fault, a minor thrust fault has been observed. The failure surface of the slide locally follows bedding planes located to the east of the anticline hinge. At the toe, the failure surface follows the minor thrust fault and at the top, it is controlled by a combination of two or three joint sets and intact rock fractures (Jaboyedoff et al., 2009).
Jones (1993) interprets the minor fault as a folded thrust fault and explains that a wedge formed by its intersection with bedding planes creates unstable blocks on the eastern flank of Turtle Mountain. Consequently, the structural geology of the mountain becomes extremely sensitive to triggering factors; freezing and thawing, river erosion at the toe and mining at the base all having been proposed (Cruden and Martin, 2007; Benko and Stead, 1998).

The purpose of the present project is to create a terrestrial 3D model of the South Peak of Turtle Mountain to complement the existing airborne LiDAR DEM. The ground resolution of the latter on flat terrain is about 0.5 m, however, due to the vertical line-of-sight, this may decrease up to 3 m, particularly on sub-vertical slopes. Such a resolution will result in the truncation of medium to high persistence discontinuities. In contrast, with a sub-horizontal line-of-sight, a terrestrial 3D model provides a higher ground resolution on sub-vertical slopes (up to 40 mm for TLS and 96 mm for TDP with an \( f = 400 \) mm lens). Preliminary observations using terrestrial and airborne LiDAR on Turtle Mountain were presented in a previous paper by the author (Sturzenegger et al., 2007b).

### 4.6.1 Composite TDP/TLS model creation

To create the terrestrial 3D model, a combination of TDP and TLS was used, thereby using the advantages of one technique to mitigate the limitations of the other. TLS is more convenient to undertake on narrow ridges, with limited vantage points, between which important changes in perspective occur. Using TLS, a single position is enough to create a point cloud of the scene. However, the TLS range is limited to about 800 metres, while the east facing scar of Turtle Mountain must be imaged from a distance greater than 2 km. Consequently, TDP with a high focal length (\( f = 400 \) mm) provides an ideal solution.

The final 3D model was built by merging point clouds and stereomodels created from 6 TLS and 4 TDP locations (Figs. 4-14b and 4-15a). Registration was achieved by surveying camera/scanner locations and 8 large high contrast coloured targets with a DGPS. The accuracy and precision of the composite 3D model is detailed in Table 4-6, estimated by comparison with the DGPS survey, which has a centimetre accuracy.
Several parameters contribute to the overall model error, including the inherent accuracy of the laser scanner, the stereomodel creation process, alignment of successive models and target recognition. The main error component in the current project resulted from the alignment process, as the challenging mountainous terrain made it sometimes impossible to obtain optimal overlap between successive adjacent models.

Table 4-6. Accuracy (mean error) and precision (standard deviation) of the composite 3D model of South Peak, Turtle Mountain, Alberta.

<table>
<thead>
<tr>
<th></th>
<th>Northing</th>
<th>Easting</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean error [m]</strong></td>
<td>0.141</td>
<td>-0.057</td>
<td>-0.084</td>
</tr>
<tr>
<td><strong>Standard deviation [m]</strong></td>
<td>0.490</td>
<td>0.603</td>
<td>1.224</td>
</tr>
</tbody>
</table>

The quality of the composite 3D model is evaluated by overlaying and comparing it with the airborne LiDAR DEM. To accomplish this, the shortest distance between each point on the 3D models and the reference airborne LiDAR DEM are computed and displayed as an error map. Figure 4-15b shows that, with the exception of a few limited areas, the two models match very well (errors up to 2-3 metres). Locally, errors up to 5 metres occur due to scattered large boulders, gullies and trees, which could not be filtered out.

The terrestrial composite 3D model has a higher ground resolution, but is frequently affected by occlusion zones at the very top of the peak, behind trees and protruding blocks, or along cracks and gullies. Depending on access, these occluded areas could be, in the future, mapped in more detail, using close-range TDP or TLS surveys.
Figure 4-15. Composite 3D model of the South Peak. (a) Oblique view of the NE side, displayed using ArcScene (ESRI Inc., 2006), (b) plane view of the error map of the whole model.
4.6.2 Discontinuity mapping

A major advantage of the terrestrial 3D model is that it allows recognition of medium and higher persistence discontinuities located on oblique to sub-vertical rock slopes, such as the failure surface and lateral boundaries of the slide, where airborne LiDAR DEM resolution is in contrast more limited. Discontinuity characterization was achieved using both the $f = 400$ mm photogrammetric stereomodel built from the base of the mountain, at a range of 2.1 km, and the close-range TLS point cloud created from locations around the mountain peak. Figure 4-16 shows selected details of these two components of the composite 3D model.

Discontinuity characterization covers the upper part of the South Peak above an elevation of 2000 m, in the Livingstone Formation (Tables 4-2 and 4-7). Figure 4-17a shows that bedding planes are clearly recognized and that cross joints have a large variability of orientations. Medium to very high persistence structures were mapped (Fig. 4-17b). Discontinuity sets J1 and J2 described by Couture (1998) and Spratt and Lamb (2005) can be recognized. S0, J2 and J4 sets were mapped by Brideau (M.-A. Brideau, personal communication, 2008). Discontinuity set J3 has not been mapped in the field by other authors, however, it was recognized on airborne DEM by Jaboyedoff et al. (2009) with a lower dip. Two possible reasons can explain this; firstly, discontinuity set J3 was mapped on the East facing scar of the South Peak, where there is very limited access for field mapping. In addition, Fig. 4-17c shows that most of the J3 discontinuities are very high to extremely high persistence surfaces (ISRM, 1978). It is possible that these surfaces represent, as discussed previously, composite surfaces combining both joints and intact rock fractures with a step-path geometry. Such features are not observed during field survey, which focus on lower persistence joints.
Figure 4-16. Components of the composite terrestrial 3D model of the South Peak. (a) photogrammetric stereomodel (draped with a digital photograph) of the upper part of the NE side of the peak (scar) built using a $f = 400$ mm lens from a distance of 2.1 km, (b) TLS point cloud (rendered using greyscale intensity values) of the SE side of the peak, surveyed from a distance of 150 metres.
4.7 Discussion

This chapter evaluates techniques for quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial digital photogrammetry and terrestrial laser scanning. The methodology is described and evaluated on a large cliff at Bridal Veil Falls where it is shown that the choice of registration method does not significantly affect plane orientation measurements. The accuracy obtained is considered adequate for discontinuity characterization on high mountain rock slopes where significant issues relate to safety, access and true representation of discontinuity networks. The potential for occlusion and orientation bias must always be considered in remote sensing discontinuity measurements, as topographical constraints will frequently prevent the optimal location of the camera/scanner. It is strongly recommended that remote-sensing methods be combined with conventional geological and structural observations and other techniques wherever possible in order to obtain comprehensive datasets.

Table 4-7. Discontinuity orientation and persistence characterization on the South Peak using terrestrial remote-sensing.

<table>
<thead>
<tr>
<th>Set name</th>
<th>Mean dip [°]</th>
<th>Mean dip direction [°]</th>
<th>Persistence</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>45</td>
<td>287</td>
<td>Medium-extremely high</td>
</tr>
<tr>
<td>J1</td>
<td>88</td>
<td>342</td>
<td>Medium-very high</td>
</tr>
<tr>
<td>J2</td>
<td>73</td>
<td>071</td>
<td>High</td>
</tr>
<tr>
<td>J3</td>
<td>76</td>
<td>130</td>
<td>Very high-extremely high</td>
</tr>
<tr>
<td>J4</td>
<td>63</td>
<td>173</td>
<td>Medium-high</td>
</tr>
</tbody>
</table>
Figure 4-17. Discontinuity characterization. (a) stereonet (lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area), (b) equivalent trace length distribution, (c) symbolic pole plot of persistence class (ISRM, 1978).
The second part of the chapter evaluates the effect of observation scale on orientation and persistence measurements using 3D LiDAR/photogrammetric models with varying ground resolutions. It is shown that scale bias can result in both a lack of measurements for a specific discontinuity set and a shift in discontinuity set orientation. In the first case, there is an orientation bias, when, at low resolution, non-persistent discontinuity sets are truncated and consequently do not appear on stereonets, their persistence being too small compared to the point spacing. The truncation threshold decreases with increasing resolution, such that when mapping from higher resolution 3D models, discontinuities which did not appear at lower resolution can now be recognized and measured. Consequently, the minimum and mean trace length of discontinuities increases with decreasing ground resolution.

The second case follows as a direct consequence of the truncation of specific joints due to resolution/scale-based orientation bias. As resolution decreases, the rock slope texture is smoothed, resulting in a shift in orientation. This second effect is illustrated on Fig. 4-9, which shows that a large feature dipping at about 45° is actually composed of multiple low persistence joints, dipping more steeply. At low resolution, the ground point spacing is too large to enable mapping of the low persistence joints and consequently, only the average 45° dipping feature will be sampled. This effect typically occurs on step-path surfaces trending at a small angle with respect to the line-of-sight of the camera/scanner. Measuring such surfaces results in an overestimation of persistence. The effects of scale bias on discontinuity orientation and persistence measurements are summarized in Table 4-8.

The preliminary empirical Eqs. 4-2 and 4-3, derived from the trend lines of Fig. 4-10, can be used as a planning tool to estimate an average persistence of discontinuities, which can be characterized with specific ground point spacing. Conversely, they can also be used to select an adequate lens focal length/spot spacing in order to characterize discontinuities of a certain size. Figure 4-10c suggests that the ground resolution/mean trace length relationship varies according to the rock type and is best fitted by a power law. Although the $R^2$ values are high, it is emphasised that the trend lines are derived
from a limited amount of values and more research on a variety of rock types is required to complement these results.

Table 4-8. Summary of scale bias effects on discontinuity orientation and persistence measurements.

<table>
<thead>
<tr>
<th>Scale bias (or observation scale)</th>
<th>Effect on discontinuity orientation measurements</th>
<th>Effect on discontinuity persistence measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Truncation of non-persistent discontinuity sets resulting in orientation bias (Fig. 4-7)</td>
<td>Truncation of non-persistent discontinuities, small compared to ground point spacing</td>
</tr>
<tr>
<td></td>
<td>Shift in discontinuity orientation, because of smoothing of step-path geometries (Figs. 4-8 and 4-9)</td>
<td>Overestimation of the length of extremely persistent features actually composed of a combination of both smaller discontinuities and intact rock fractures. This results from the smoothing of the step-path geometries at low resolution (Fig. 4-9).</td>
</tr>
</tbody>
</table>

As stated previously, at low ground resolution, some structural features could be mistaken as extremely persistent discontinuities, while in reality they represent composite step-path surfaces containing a series of non-persistent discontinuities. In this chapter, two types of step-path geometry are described from LiDAR and photogrammetric models. The question of which persistence value, i.e., which ground resolution to use, should be asked. Clearly, in terms of slope stability, persistent and fully developed features, already recognizable on low resolution 3D models, are more hazardous than shorter ones, whether they are single persistent discontinuities or composite surfaces with a step-path geometry. However, a detailed characterization at higher resolution of both discontinuities and intact rock bridges will provide a better understanding of the discontinuity/rock mass strength properties, such as cohesion and friction in addition to the importance of brittle fracture and hence tensile strength of the rock mass.

The third part of the chapter illustrates the creation of a terrestrial 3D model of the South Peak of Turtle Mountain, using a combination of terrestrial digital photogrammetry and terrestrial laser scanning. TLS is convenient on sharp ridges, where accessibility and rapid changes in perspective limit the use of TDP (which require two or more camera
stations). In contrast, unlike most routinely available TLS, TDP allows building of high resolution stereomodels at a range exceeding 2 km, when a large focal length \((f = 200-400 \text{ mm})\) is used. The use of high focal length \((f = 400 \text{ mm})\) lenses in digital photogrammetry has to the author’s knowledge rarely been documented in the geotechnical literature and this chapter clearly shows their significant potential for rock slope and landslide investigations. Consequently, the case study data presented highlights new opportunities for detailed discontinuity characterization, using medium-range (>300 m) to long-range (>1000 m) terrestrial digital photogrammetry. Such techniques as illustrated by the characterization of discontinuities on the South Peak can be extremely useful in mapping medium- to extremely persistent discontinuities that often play an important role in the stability of large inaccessible mountain slopes or open-pit walls.

The quality of a site investigation will benefit significantly from information collected at different observation scales, from traditional field outcrop to remote sensing mapping. Airborne LiDAR, although presenting a lower density of spatial data provide a more comprehensive (less occlusion) model of sub-horizontal to oblique slopes. The author stress that a combination of complementary terrestrial and airborne remote sensing techniques is optimal in the generation of remote sensing models of large landslides. Such models should be incorporated as routine tools in landslides investigations.

4.8 Conclusion

Field sampling methods are currently restricted to low persistence discontinuities (scanline surveys) or large scale features (airborne photographs or DEM survey). Typically, during scanline surveys, trace lengths longer than 10-15 metres can only be approximated. At the other end of the spectrum, airborne discontinuity surveys are limited by resolution, especially on steep slopes. Terrestrial remote sensing techniques can increase the ground resolution to 5-10 cm, which represents high density of spatial data on sub-vertical to oblique slopes, allowing characterization of medium and higher persistence discontinuities.

Wherever possible, it is suggested to select an appropriate ground resolution to avoid scale bias effects on discontinuity orientation and persistence measurements.
However, lower resolution 3D models should not be completely discarded as they can provide important information on large composite features. Indeed, terrestrial remote sensing may be particularly well-suited for geotechnical discontinuity characterization on large rock slopes and landslides, as they allow characterization of medium to extremely high persistence composite features, which are likely to play a major role in slope stability.

The choice of an adequate ground resolution will also be crucial for the creation of discrete fracture network (DFN) models (Elmo et al., 2007). Indeed, they can generate either an abundance of low persistence discontinuities (high resolution) or a smaller density of larger persistence discontinuities (low resolution). In the first case, the model quantifies rock mass properties such as strength or permeability, while in the second case, they characterize the structures of a rock entity that may be critical to slope failure. The purpose of the use of DFN models should be considered when selecting the scale of discontinuities to be characterized.

4.9 Acknowledgements

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4.10 Reference list


CHAPTER 5
TERRESTRIAL REMOTE SENSING-BASED
ESTIMATION OF MEAN TRACE LENGTH,
TRACE INTENSITY AND BLOCK
SIZE/SHAPE

The following chapter has been submitted as:


5.1 Abstract

The objective of this chapter is to investigate the potential of terrestrial remote sensing techniques for the estimation of mean trace length, trace intensity and block size/shape. Sampling window mapping is applied, adapted for terrestrial remote sensing data, and compared with field-based scanline measurements. A so-called “topographic” circular sampling window is introduced which, when used in combination with trace count estimators, provides the most accurate estimation of trace intensity and mean trace length. Indeed, this type of window minimizes sampling bias, avoiding underestimation of discontinuity frequency and overestimation of trace length. The quantification of block size/shape distribution through the generation of discrete fracture network (DFN) models highlights the importance of various issues and sampling bias effects contributing to the overall uncertainty associated with the characterization of discontinuity parameters. A number of recommendations, based on an initial set of DFN models, are suggested to optimize remote sensing based quantification of mean trace length, trace intensity and block size/shape.

5.2 Introduction

Terrestrial remote-sensing techniques, which include terrestrial digital photogrammetry (TDP) and terrestrial laser scanning (TLS) have allowed significant
improvement in our ability to measure rock mass discontinuity properties. Characterization of discontinuity location, orientation, persistence, spacing and roughness have been described by many authors, including Roberts and Poropat (2000), Feng and Roeshoff (2004), Kemeny and Donovan (2005), Gaich et al. (2006) and Haneberg (2007). Sturzenegger and Stead (2009a) highlighted the benefits of these techniques for meaningful estimation of discontinuity set orientation, accurate quantification of discontinuity size up to extremely high-persistence and for practical measurement of the location of individual discontinuities. This chapter complements previous work focusing on the estimation of discontinuity frequency, mean trace length and block size/shape, using both TDP and TLS datasets.

Discontinuity frequency can be expressed by a variety of parameters, including density, intensity and spacing. For a comprehensive review on spacing, the reader should refer to Priest and Hudson (1981), Palmström (1982) and Priest (1993). Discontinuity density represents the number of discontinuity centroids per unit volume, area or length. Discontinuity intensity is defined as the total discontinuity persistence, i.e., trace length or discontinuity surface, per area or volume, respectively.

To address the ambiguity of multiple definitions of discontinuity density and intensity, Dershowitz and Herda (1992) developed a unified system of discontinuity frequency measures. This system defines fracture frequency in terms of the dimensions of the sampling region (e.g. scanline, trace map, volume) and the dimensions of the features (e.g. count, trace, surface). The specific terminology used within the framework of the Discrete Fracture Network (DFN) code FracMan (Golder Associates, 2009; Dershowitz et al., 1998) is as follows. Fracture density is defined as the number of fractures per unit volume of rock mass ($P_{30}$), the number of traces per unit area of a sampling plane ($P_{20}$) or the number of fractures per unit length of scanline or borehole ($P_{10}$). Fracture intensity is defined as the area of fractures per unit volume of rock mass ($P_{32}$), the length of fracture traces per unit area of sampling surface ($P_{21}$) or as the linear intensity ($P_{10}$).

The volumetric fracture intensity ($P_{32}$) is a true non-directional rock mass property. Although it cannot be directly measured, it can be inferred from discontinuity
areal \((P_{21})\) or linear \((P_{10})\) intensity on the basis of linear correlations (Dershowitz et al., 2000):

\[
P_{32} = C_{31} P_{10} \tag{5-1}
\]

\[
P_{32} = C_{32} P_{21} \tag{5-2}
\]

where \(C_{31}\) and \(C_{32}\) are constants of proportionality depending on fracture orientation, radius size distribution and the orientation of the sampling window or scanline.

Measurements of discontinuity trace length and areal frequency \((P_{20} \text{ or } P_{21})\) can be achieved using sampling windows. Bias associated with this sampling technique have been discussed by several authors and include orientation bias (Terzaghi, 1965), length bias, truncation, censoring (Zhang and Einstein, 1998), \(f\)-bias (Priest, 2004) and scale bias (Ortega et al., 2006; Sturzenegger and Stead, 2009b). The methods proposed by Pahl (1981) and Kulatilake and Wu (1984a) to estimate trace length, using rectangular sampling windows, are applicable to a discontinuity set with a single orientation value and an orientation described by a probabilistic distribution, respectively. These methods consider both length bias and censoring. Kulatilake and Wu (1984b) estimate trace density, based on the probability that the midpoint of a given trace lies inside the selected window. However, this method is trace length distribution-dependent, and the underlying distribution of trace length is generally unknown.

Mauldon (1998) and Zhang and Einstein (1998) propose a method to estimate the true trace length distribution (mean and standard deviation) using a circular window of finite size. The true trace length distribution differs from the measured distribution, which considers only a biased sample (window) of the entire trace population. This method is applicable to traces with arbitrary orientation distributions and can be used to estimate the true mean trace length of more than one set of discontinuities. As for other trace length distribution-free end-point estimators, length bias and censoring are avoided. The method uses the number of traces \((N)\) intersecting the window, the number of traces \((N_0)\) with both ends censored (transecting), and the number of traces \((N_2)\) with both ends observed (contained). The true mean trace length \((\mu_t)\) and true standard deviation \((\sigma_t)\) are expressed as:
where \( c \) is the radius of the circular window and \((COV)_m\) is the coefficient of variation of the measured trace lengths, i.e., the ratio of the measured standard deviation to the measured mean. Measured and true COV are assumed to be the same. Similarly, it is assumed that the measured and true trace length distributions have the same form. Zhang and Einstein (2000) implement the above calculated true trace length distribution in an equation by Warburton (1980), which considers a stereological relationship between chords (traces measured on sampling windows) and associated diameters for specific discontinuity sets, discontinuity shape being assumed circular. Problems involving elliptical discontinuities have been solved by Zhang et al. (2002).

Mauldon et al. (2001) developed a further method, using circular scanlines and a circular window, to estimate trace parameters. This method is based on the number, \( m \), of joint endpoints inside a circular window and the number, \( n \), of joint intersections with a circular scanline (see Table 5-2). Trace density (\( \rho \)), trace intensity (\( I \)) and true mean trace length (\( \mu \)) are then expressed as:

\[
\rho = \frac{m}{2\pi r^2} \quad (5-5)
\]

\[
I = \frac{n}{4r} \quad (5-6)
\]

\[
\mu = \frac{\pi r \left( \frac{n}{m} \right)}{2} \quad (5-7)
\]

where \( r \) is the radius of the circular window.

Using the above mentioned techniques, it is important that the size of any circular window be defined so that \( N_0 \neq N \) (all joints are not censored at both ends) and \( N_2 \neq N \) (all joints are not contained within the window) (Zhang and Einstein, 1998). When applying the method of Mauldon and co-workers, the selected windows should be larger than the mean block size and a minimum of 30 “\( m \)” counts are recommended to reduce
the variability of estimates (Rohrbaugh et al., 2002). In addition, it is suggested that multiple windows of the same size and at different locations be used.

Song (2006) noted that a sufficient number of traces sometimes cannot be sampled on a single planar sampling window and suggested a method to estimate areal density and mean trace length on non-planar surfaces. In contrast to the apparent areal frequency estimator mentioned previously, the proposed method includes an orientation variable, representing the angle between the sampling window and the discontinuity set orientation. Consequently, this method is only applicable to a randomly located parallel disc model, although a variation of discontinuity orientation within the set can be tolerated up to a Fisher K value of 5.

Mean block size and shape quantification have been discussed by several authors, including Palmström (1996 and 2005) and Cai et al. (2004). Sturzenegger et al. (2007) review these methods and propose a technique to visualize average blocks in 3D. Abellan et al. (2006) and Pötsch et al. (2006) show how specific blocks can be characterized by intersecting discontinuities on TLS/TDP 3D models. While such deterministic techniques are useful, it is often more realistic to provide block size and shape distributions (Kalenchuk et al., 2006), which can be obtained using discrete fracture network (DFN) models.

DFN models represent very powerful tools for building realistic fracture networks, assuming varying spatial models, fracture size and fracture orientation distributions. The stochastic nature of the DFN model generation process is such that there are an infinite number of possible realisations of the 3D discontinuity system based on the mapped data. The mapping process is itself random due to the nature of how fractures are presented in available windows. With the exception of fully explicit modelling of an individual fracture or simplified fracture sets, the stochastic approach provides the best option for creating realistic geometric models of fracturing. In particular, they avoid the use of simplistic fracture networks assuming ubiquitous, infinite length fractures and fracture sets with constant orientation (Rogers et al., 2006).

A primary objective of this chapter is to investigate the potential of terrestrial remote sensing techniques for the estimation of mean trace length, trace intensity and
block size/shape. Three remote sensing sampling window types, including planar and topographic windows, are evaluated and compared with field-based scanline measurements. A topographic discontinuity survey window is introduced representing an adaptation of the existing sampling window technique for application using remote sensing data. A preliminary example of integration of close-range remote sensing data into DFN models is then provided with emphasis on a quantitative characterization of block size/shape parameters. The uncertainty associated with DFN model generation using both field-based scanline and remote sensing window mapping is discussed and a number of recommendations suggested in consideration of the uncertainty associated with the estimation of mean trace length, trace intensity and block size/shape.

5.3 Fracture frequency and block size estimation from 3D remote sensing models

Discontinuities delineated on TLS/TDP 3D models are considered planar and circular. Although it is possible that they have other shapes (Zhang et al., 2002; Zhang and Einstein, 2009), characterization on 3D models often does not allow for their definition, and consequently a circular shape is usually assumed. To improve data interpretation, mapping of discontinuities on remote sensing imagery was undertaken manually, without the use of automatic recognition software.

TLS point clouds were acquired at four sites. Ground point spacing ranges between 6 and 22 mm. Table 5-1 provides a summary of these sites including location, rock type, geological age, Geological Strength Index (GSI) estimate (Hoek and Brown, 1997; Hoek et al., 2002), slope geometry and range of acquired imagery. Figures 5-1 and 5-2 show photographs of each outcrop accompanied by discontinuity orientations and sets. For further details regarding joint set orientation and persistence measured using TLS, TDP and conventional field methods for these sites, the reader is referred to Sturzenegger and Stead (2009a).
Table 5-1. Road cut characteristics (based on Sturzenegger and Stead, 2009a).

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Rock type</th>
<th>Age</th>
<th>GSI - structure</th>
<th>Road cut height/length [m]</th>
<th>Average slope dip/dip direction [°]</th>
<th>Average range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Seymour (Fig. 5-1a)</td>
<td>North of Vancouver (Canada), along the road leading to the Mount Seymour ski resort</td>
<td>Quartz diorite intrusive rock from the Coast Plutonic Complex (Massey et al., 2005). Some younger basaltic dykes intrude the rock mass in its central and south-western part</td>
<td>Mid-Cretaceous</td>
<td>[60-70] - blocky</td>
<td>19/80</td>
<td>74/137</td>
<td>31</td>
</tr>
<tr>
<td>Manning Park (Fig. 5-1b)</td>
<td>Manning Provincial Park, 170 km east of Vancouver (Canada), along Highway 3</td>
<td>Slate with lenses of sandstone from the Jackass Mountain Group (Massey et al., 2005)</td>
<td>Lower Cretaceous</td>
<td>[40-50] - schistose</td>
<td>14/120</td>
<td>70/200</td>
<td>29</td>
</tr>
<tr>
<td>Saskatchewan Crossing (Fig. 5-1c)</td>
<td>10 km south of Sask. Crossing, Canadian Rocky Mountains, along Highway 93</td>
<td>Limestone and derived dolomite from the Eldon Formation (Aitken, 1968)</td>
<td>Middle Cambrian</td>
<td>[65-75] - blocky</td>
<td>13/70</td>
<td>73/074</td>
<td>30</td>
</tr>
<tr>
<td>Murrin Lake (Fig. 5-2)</td>
<td>50 km north of Vancouver (Canada), along Highway 99</td>
<td>Granodiorite from the Coast Plutonic Complex (Massey et al., 2005)</td>
<td>Mid-Cretaceous</td>
<td>[85-95] - massive</td>
<td>37/41</td>
<td>80/328</td>
<td>163</td>
</tr>
</tbody>
</table>
Figure 5-1. Road cuts with associated discontinuity orientations and sets measured on TLS point clouds. (a) Mount Seymour, (b) Manning Park, (c) Saskatchewan Crossing. The large empty squares on the stereonet (a) represent discontinuity traces longer than 5.5 m.
Figure 5-2. Murrin Lake road cut with associated discontinuity orientations and sets measured on TLS point clouds. The large empty squares on the stereonet represent persistent/critical discontinuities.

5.3.1 Field-based scanline mapping

Trace intensity and mean trace length have been measured in the field along scanlines, for comparison with remote sensing circular window mapping. Mean trace length is the average length of all discontinuities of a specific set intersecting the scanline. Trace intensity ($P_{10}$) is the number of trace intersections per linear unit and is scanline orientation dependant. Equation 5-8 relates the observed frequency ($\lambda_s$) to the linear frequency ($\lambda$) along a line normal to a discontinuity set (Priest, 1993).

$$\lambda_s = \lambda \cos \delta$$  \hspace{1cm} (5-8)

where $\delta$ is the acute angle between the scanline and the set normal.

With field-based scanline mapping, orientation bias has been minimized using several scanlines in various directions. Censoring does not occur because all sampled traces are contained within the exposure and truncation is minimal for the rare traces smaller than approximately 10 cm.
5.3.2 Trace intensity and mean trace length estimation using remote sensing circular windows

Although scanline mapping can be adapted for application in TLS/TDP 3D models, Sturzenegger and Stead (2009a) demonstrated that it may provide a limited number of measurements, particularly when data is acquired at long range. In addition, these authors suggest that window mapping is more appropriate in order to fully use terrestrial remote sensing data collected for the higher part of rock slopes. Finally, based on computer simulations, Rohrbaugh et al. (2002) also show that measurements using linear scanlines underestimate trace intensity, while circular windows are more accurate. In recognition of this work, the author use circular windows only in this study (Fig. 5-3).

Circular windows are preferred to rectangular cells, because they eliminate orientation bias along the mapped surface (Mauldon et al., 2001). Orientation bias in the third dimension can be avoided by using several circular windows on exposures with various orientations. As noted in Section 5.2, both censoring and length bias are minimized when using window mapping. Truncation is minimized when using a low cutoff value. Circular windows measure areal trace intensity ($P_{21}$), which is window orientation dependant. Equation 5-9 relates the apparent frequency, $\lambda_{ar}$, and the “true” frequency, $\lambda_t$, of a discontinuity set (Priest, 1993):

$$\lambda_{ar} = \lambda_t \sin \gamma$$

(5-9)

where $\gamma$ is the angle between the rock slope normal and discontinuity set normal.

In this chapter, remote sensing circular windows are used on TLS/TDP 3D models and compared to field-based scanline measurements. A study of the use of 3 types of remote sensing circular windows is undertaken for each of the four field sites (Table 5-1). Windows with various radii are used in order to optimize window size in the quantification of trace intensity and mean trace length on 3D models. Window Type 1 (Table 5-2) is based on the use of a planar circle having the average rock slope orientation. Estimates of trace intensity are obtained by dividing the sum of all trace segments enclosed within the window by the circle area. Mean trace length is calculated as the average length of all discontinuities intersecting, transecting or contained in the window. Window Type 2 uses the same planar circle, but intensity and true mean trace
length estimates are obtained using the methods presented by Mauldon et al. (2001) and introduced in Sect. 5.2 (Fig. 5-3b and Table 5-2).

Finally, Window Type 3 is an application of the method proposed by Mauldon et al. (2001) on a topographic window, which conforms to the relief of the rock slope (Figs. 5-3c, 5-3d and Table 5-2). Using a topographic window allows consideration of discontinuity traces within a buffer zone on both sides of a sampling window (Fig. 5-3e). This approach is considered a practical option as natural or man-made rock slopes are not perfectly planar and considering only discontinuities intersecting a planar window is expected to result in measurement bias (see Sect. 5.4.2).

On a topographic window, discontinuity traces are not straight lines, but the application of the method of Mauldon and co-workers allows consideration of only trace extremities within the window and intersections with the window perimeter. In order to apply Eqs. 5-5 to 5-7, which were initially developed for planar circular windows, it is assumed that trace extremities and intersections on topographic windows can be projected onto a circle whose area and perimeter are equivalent to the respective area and perimeters of the base of a cylinder containing the topographic window (Fig. 5-3e). As suggested previously, this assumption is considered a practical solution in order to reduce the expected trace measurement bias.
Figure 5-3. Remote sensing circular sampling windows on TLS/TDP 3D models. (a) Extraction of the window from a 3D model. (b) Planar window with the traces of two intersecting discontinuities. Discontinuity intersections are used for Window Type 1 estimation of trace intensity. The number of endpoints contained within (white spots) and crossing (black spots) the window is used for the Window Type 2 estimator by Mauldon et al. (2001). (c) Topographic circular window (Type 3) with the same intersecting discontinuities. (d) Oblique view showing the relief of the topographic window. (e) Cylinder illustrating the buffer zone on both sides of a topographic window. Trace extremities and intersections on topographic windows can be projected onto the grey transparent circle representing the base of the cylinder.
<table>
<thead>
<tr>
<th>Circular window</th>
<th>Trace intensity $[\text{m/m}^2]$</th>
<th>Mean trace length $[\text{m}]$</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 (planar)</td>
<td>$P_{21} = \sum \frac{l}{\pi r^2}$</td>
<td>$MTL = \sum \frac{L}{N}$</td>
<td><img src="image1" alt="Illustration of Type 1" /></td>
</tr>
<tr>
<td>Type 2 (planar)</td>
<td>$I = \frac{n}{4r}$</td>
<td>$\mu = \frac{\pi r}{2} \left( \frac{n}{m} \right)$</td>
<td><img src="image2" alt="Illustration of Type 2" /></td>
</tr>
<tr>
<td>Type 3 (topographic)</td>
<td>$I = \frac{n}{4r}$</td>
<td>$\mu = \frac{\pi r}{2} \left( \frac{n}{m} \right)$</td>
<td><img src="image3" alt="Illustration of Type 3" /></td>
</tr>
</tbody>
</table>

$l$ = number of traces
$L$ = number of traces
$N$ = number of traces
$r$ = window radius

$m$ = circle
$n$ = circle
$r$ = window radius
5.3.3 Block size and shape

In this chapter, block size distribution is obtained from DFN models generated using FracMan (Fig. 5-4) (Golder Associates, 2009) and created following the methodology adopted by Elmo (2006). The required parameters for the generation of DFN models are discontinuity orientation distribution, trace length distribution and fracture intensity. Calibration of the DFN models is achieved by comparing and adjusting, using virtual FracMan scanlines/windows, the orientation, size, intensity and pattern of the simulated fracture traces with those measured along scanlines in the field or along remote sensing circular windows on TLS/TDP 3D models. To optimize the calibration procedure, generated discontinuity set parameters should be compared using virtual FracMan scanlines/windows of similar size, shape and orientation as the one used to map discontinuities in the field or on 3D models. It is worth mentioning that Eq. 5-8 and 5-9 should not be applied here, since the virtual FracMan scanlines/windows have the same orientation as the scanlines/windows used in the field or on TLS/TDP 3D models.

The FracMan code allows for the 3D visualisation of blocks defined by intersecting discontinuities in the DFN model, employing either an implicit cell mapping algorithm or a more conventional explicit block search algorithm (Dershowitz and Carvalho, 1996). While the latter provides an accurate estimate of block shape and volume, its use is better suited for the kinematic assessment of block stability. The cell mapping algorithm is optimized to provide an initial estimate of the natural rock fragmentation. The cell mapping algorithm works by initially identifying all the fracture intersections within the specified grid elements. This results in a collection of grid faces and connection information, which is then used to construct a rock block of contiguous grid cells. Work is ongoing to further develop the cell mapping algorithm to obtain an explicit representation of the block volumes by unfolding the implicit block to the fracture element mapped on the grid cell elements. Note that in the current study, only blocks internal to the fracture model (i.e., not intersected by a face) are considered when assessing the size and shape distributions of the mapped rock masses.
This section reviews the procedure used to incorporate TLS/TDP 3D model measurements of discontinuity parameters into FracMan. Discontinuity mapping on TLS/TDP 3D models is achieved manually and orientation, trace length and position measurements directly exported, as described in Sturzenegger and Stead (2009a). Persistent discontinuities likely to play an important role are recorded and inserted into the DFN model as deterministic entities. The choice of such features and their importance is based on geological and geological engineering judgment. Fracture termination and shape may also be incorporated in DFN models.

Discontinuity orientation measurements are plotted on stereonets and contour plots used to recognize discontinuity sets, determine mean dip, mean dip direction and Fisher K value. If the discontinuity sample or components of it do not cluster around preferred orientations, it is possible to use the “bootstrap” option in FracMan. This is a statistical method based upon multiple random sampling with replacement from an

Figure 5-4. Discrete fracture network (DFN) model generated based on the Mount Seymour remote sensing data. The various colors refer to different discontinuity sets.
original sample to create a pseudo-replicate of fracture orientations. The “bootstrap” option requires a dispersion parameter to be specified; the smaller the assumed dispersion, the more dispersed the values. This dispersion parameter behaves in the same way as a Fisher distribution, with bootstrap poles as centers around which values are dispersed rather than a single Fisher pole.

Once discontinuity sets are defined, their trace intensity ($P_{21}$) is estimated, using remote sensing circular Window Type 3 and Eq. 5-6, and the true mean trace length ($\mu$) calculated using Eq. 5-7. Note that using this approach, the true trace length standard deviation cannot be quantified. However, this descriptive parameter is not necessary for a negative exponential distribution, which is entirely defined by the mean. The validity of the assumed distribution is affected by the assumed fracture cut-off in the field. In this study, trace length measurements follow an apparent lognormal distribution. However, it has been shown that depending on the observation scale, the truncation cut-off is shifted, because discontinuities smaller than a certain dimension are not sampled (Sturzenegger and Stead, 2009a and 2009b; Sturzenegger et al., 2009). Consequently, the apparent lognormal distribution shifts depending on the observation scale. This effect is illustrated in Fig. 5-5, based on photogrammetric data. In such a case, using negative exponential distributions is recommended, allowing one to account for truncation bias induced by the observation scale. Where evidence exists for a different trace length distribution form, the measured standard deviation could be derived from trace length distributions and the true standard deviation calculated using Eq. 5-4 (Zhang and Einstein, 2000).
Figure 5-5. Histogram illustrating the apparent log-normal trace length distributions of two sets of photogrammetric measurements (after Sturzenegger et al., 2009). When the model resolution increases (focal length from 100 to 400 mm), the trace length distribution and truncation cut-off are shifted towards lower values. The dotted line shows a negative exponential distribution, which fits all data.

5.4 Comparison of remote sensing circular window types and sizes

A study on a number of remote sensing circular windows has been undertaken at the four road cuts in order to investigate the optimal window type and size. The radius of the windows varies from 2 to 15 m in order to respect the guideline summarized in Section 5.2. To facilitate comparison, measurements were done on the entire trace population, which includes 2 or 3 discontinuity sets (Figs. 5-1 and 5-2).
5.4.1 Comparison between remote sensing planar Windows Type 1 and 2

Examination of Table 5-3 and Figs. 5-6a and 5-6b suggests that sampling Window Types 1 and 2 provide consistent estimation of trace intensity, with an average difference of 15%. Higher differences occur for samples MS2, SC3 and ML5 which do not have the minimum of 30 “m” counts recommended by Rohrbaugh et al. (2002), and overestimate trace intensity compared to Window Type 1. This means that there are insufficient traces contained within the window, i.e., too many traces intersecting it, and consequently, the window should be enlarged. In contrast, sample MP4 significantly underestimates intensity compared to Window Type 1, possibly because the window radius is too large with respect to the mean block size/GSI. Indeed, sample MP4 was obtained in the Manning Park road cut, whose estimated GSI is lower (Table 5-1). Consequently, the size of a window may have to be adapted to the mean block size/GSI.

Figures 5-6c and 5-6d show the mean trace length estimations. The results from Window Types 1 and 2 closely agree, with an average difference of 12%. Larger differences are similarly observed for samples MP4 and ML5 due to an inappropriate window size with respect to the mean block size/GSI.

The results of the comparison between Window Types 1 and 2 are in agreement with Mauldon et al. (2001) and Rohrbaugh et al. (2002), who previously showed that their estimator provides similar accuracy in the estimation of trace intensity as $P_{21}$. In order to improve measurement reliability, these authors recommended averaging of the results from several windows within the same rock mass. In addition, as stated in Section 5.2 for improved accuracy, the window radius should be larger than the block size and a minimum of 30 “m” counts is recommended.
Table 5-3. Remote sensing circular window parameters and results. All windows were achieved on TLS point clouds.

<table>
<thead>
<tr>
<th>Window type</th>
<th>Location</th>
<th>Window radius [m]</th>
<th>“m” count</th>
<th>“n” count</th>
<th>Trace density ($P_{20}$) [1/m]</th>
<th>Trace intensity ($P_{21}$) [m/m²]</th>
<th>Mean Trace length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mt. Seymour (MS6)</td>
<td>6</td>
<td>n/a</td>
<td>n/a</td>
<td>1.98</td>
<td>2.19</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Mt. Seymour (MS4)</td>
<td>4</td>
<td>n/a</td>
<td>n/a</td>
<td>1.95</td>
<td>2.49</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Mt. Seymour (MS2)</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>1.22</td>
<td>3.26</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Manning Park (MP4)</td>
<td>4</td>
<td>n/a</td>
<td>n/a</td>
<td>1.64</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Manning Park (MP2)</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
<td>1.49</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Sask. Crossing (SC5)</td>
<td>5</td>
<td>n/a</td>
<td>n/a</td>
<td>1.63</td>
<td>2.69</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Sask. Crossing (SC3)</td>
<td>3</td>
<td>n/a</td>
<td>n/a</td>
<td>1.45</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Murrin Lake (ML15)</td>
<td>15</td>
<td>n/a</td>
<td>n/a</td>
<td>0.49</td>
<td>4.06</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Murrin Lake (ML10)</td>
<td>10</td>
<td>n/a</td>
<td>n/a</td>
<td>0.52</td>
<td>4.25</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Murrin Lake (ML5)</td>
<td>5</td>
<td>n/a</td>
<td>n/a</td>
<td>0.59</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Mt. Seymour (MS6)</td>
<td>6</td>
<td>206</td>
<td>48</td>
<td>0.91</td>
<td>2.00</td>
<td>2.20</td>
</tr>
<tr>
<td>2</td>
<td>Mt. Seymour (MS4)</td>
<td>4</td>
<td>74</td>
<td>32</td>
<td>0.74</td>
<td>2.00</td>
<td>2.72</td>
</tr>
<tr>
<td>2</td>
<td>Mt. Seymour (MS2)</td>
<td>2</td>
<td>12</td>
<td>12</td>
<td>0.48</td>
<td>1.50</td>
<td>3.14</td>
</tr>
<tr>
<td>2</td>
<td>Manning Park (MP4)</td>
<td>4</td>
<td>107</td>
<td>15</td>
<td>1.06</td>
<td>0.94</td>
<td>0.88</td>
</tr>
<tr>
<td>2</td>
<td>Manning Park (MP2)</td>
<td>2</td>
<td>23</td>
<td>13</td>
<td>0.92</td>
<td>1.63</td>
<td>1.78</td>
</tr>
<tr>
<td>2</td>
<td>Sask. Crossing (SC5)</td>
<td>5</td>
<td>89</td>
<td>31</td>
<td>0.57</td>
<td>1.55</td>
<td>2.74</td>
</tr>
<tr>
<td>2</td>
<td>Sask. Crossing (SC3)</td>
<td>3</td>
<td>31</td>
<td>21</td>
<td>0.55</td>
<td>1.75</td>
<td>3.19</td>
</tr>
<tr>
<td>2</td>
<td>Murrin Lake (ML15)</td>
<td>15</td>
<td>165</td>
<td>25</td>
<td>0.12</td>
<td>0.42</td>
<td>3.57</td>
</tr>
<tr>
<td>2</td>
<td>Murrin Lake (ML10)</td>
<td>10</td>
<td>80</td>
<td>18</td>
<td>0.13</td>
<td>0.45</td>
<td>3.53</td>
</tr>
<tr>
<td>2</td>
<td>Murrin Lake (ML5)</td>
<td>5</td>
<td>24</td>
<td>14</td>
<td>0.15</td>
<td>0.70</td>
<td>4.58</td>
</tr>
<tr>
<td>3</td>
<td>Mt. Seymour (MS6)</td>
<td>6</td>
<td>302</td>
<td>67</td>
<td>1.335</td>
<td>2.79</td>
<td>2.09</td>
</tr>
<tr>
<td>3</td>
<td>Mt. Seymour (MS4)</td>
<td>4</td>
<td>105</td>
<td>35</td>
<td>1.044</td>
<td>2.44</td>
<td>2.33</td>
</tr>
<tr>
<td>3</td>
<td>Mt. Seymour (MS2)</td>
<td>2</td>
<td>28</td>
<td>22</td>
<td>1.114</td>
<td>2.75</td>
<td>2.47</td>
</tr>
<tr>
<td>3</td>
<td>Manning Park (MP4)</td>
<td>4</td>
<td>149</td>
<td>29</td>
<td>1.482</td>
<td>1.81</td>
<td>1.22</td>
</tr>
<tr>
<td>3</td>
<td>Manning Park (MP2)</td>
<td>2</td>
<td>41</td>
<td>15</td>
<td>1.631</td>
<td>1.88</td>
<td>1.15</td>
</tr>
<tr>
<td>3</td>
<td>Sask. Crossing (SC5)</td>
<td>5</td>
<td>123</td>
<td>33</td>
<td>0.783</td>
<td>1.65</td>
<td>2.11</td>
</tr>
<tr>
<td>3</td>
<td>Sask. Crossing (SC3)</td>
<td>3</td>
<td>49</td>
<td>29</td>
<td>0.867</td>
<td>2.42</td>
<td>2.79</td>
</tr>
<tr>
<td>3</td>
<td>Murrin Lake (ML15)</td>
<td>15</td>
<td>239</td>
<td>29</td>
<td>0.169</td>
<td>0.48</td>
<td>2.86</td>
</tr>
<tr>
<td>3</td>
<td>Murrin Lake (ML10)</td>
<td>10</td>
<td>128</td>
<td>22</td>
<td>0.204</td>
<td>0.55</td>
<td>2.70</td>
</tr>
<tr>
<td>3</td>
<td>Murrin Lake (ML5)</td>
<td>5</td>
<td>29</td>
<td>21</td>
<td>0.185</td>
<td>1.05</td>
<td>5.69</td>
</tr>
</tbody>
</table>
5.4.2 Planar versus topographic remote sensing window types

Figures 5-6a and 5-6c show that trace intensity estimated using Window Type 3 is consistently higher than that measured using types 1 and 2, whereas discontinuity mean trace length estimation is often smaller using Window Type 3. This is a consequence of the bias associated with the use of planar windows on TLS/TDP 3D models. Indeed, discontinuities shorter than the dimensions of rock face irregularities are under-sampled, as they are not sufficiently persistent to intersect the planar window (Fig. 5-7b).
Discontinuities sub-parallel to the window are also less likely to intersect it and create a trace (Fig. 5-7b).

As can be observed in Fig. 5-6b, the differences between Window Types 1/2 and 3 vary widely being dependent on numerous parameters, including rock slope relief, discontinuity persistence and discontinuity orientation. The combined influence of these parameters on mean trace length and intensity estimation is complex. For example, where the topographic circular window on Fig. 5-7 (ML10) has a significant relief, the omitted discontinuities are non-persistent and their orientation is predominantly sub-parallel to the planar window. According to Figs. 5-6a and 5-6b, for this particular sample, the omission of these discontinuities does not have a significant effect on trace intensity measurement, but does, however, has a more significant effect on mean trace length estimation (Figs. 5-6c and 5-6d). On average, trace intensity differences (diff. 1-3 or 2-3) are 38 and 39%, respectively, and mean trace length differences (diff. 1-3 or 2-3) are 19 and 22%, respectively.
5.4.3 Remote sensing window size comparison

A study of the influence of window size on trace intensity and true mean trace length has been undertaken using topographic circular windows and the method of Mauldon and co-workers. A similar study using conventional field-based windows has been previously presented by Rohrbaugh et al. (2002) using planar circular windows. Figure 5-8 shows that such estimations are subject to some variability, particularly concerning trace intensity estimation. In addition, unreliable results are to be expected when the minimum of 30 “m” counts is not obtained (MP1 and ML5). However, for each field site, the standard deviation of both trace intensity and mean trace length measurements does not exceed 16% of the respective mean values.
Figure 5-8. Estimates of trace intensity and mean trace length using remote sensing topographic circular windows with varying radius.

5.5 Comparative quantification of mean trace length, trace intensity and block size/shape

A comparative study using both field-based scanline and remote sensing Window Type 3 mapping has been undertaken at the Mount Seymour road cut. In order to provide input data for the FracMan models, discontinuity intensities and mean trace lengths are determined for each discontinuity set separately. Mapping on remote sensing imagery has been done at two levels of detail on the same 3D model. Level 1 corresponds to the “usual” mapping of the discontinuities down to a truncation cut-off equal to approximately 50 cm. It allows for the characterization of the general structure of the outcrop and definition of discontinuity sets. Level 2 utilizes a smaller sampling window and measures discontinuities down to a truncation cut-off equal to approximately 30 cm; this requires special care in the mapping of a higher density of fractures.

5.5.1 Mean trace length and trace intensity

Field-based scanline and remote sensing window mapping results are presented in Table 5-4 and Fig. 5-9 highlighting significant differences in mean trace length
estimation. Differences in trace intensity are more difficult to assess, as scanlines consider the number of intersections per unit length of line, whereas windows allow recording of the cumulative length of traces per unit area. In order to ensure proper comparison, the $P_{21}$ of FracMan generated discontinuity sets, based on field scanline data, have also been measured using virtual FracMan windows. Similarly, the $P_{10}$ of FracMan generated sets, based on remote sensing window data, have also been measured using virtual FracMan scanlines. It is very noticeable that remote sensing data provide significantly lower estimations of the trace intensity than field measurements. In addition, along the field scanline, J1 is recorded with a lower intensity than J2, while when using the remote sensing circular windows, the reverse is observed. It should be noted that the FracMan bootstrap tool was used in order to include the large number of randomly oriented discontinuities mapped using the remote sensing window and consequently, the generated bootstrap discontinuity “set” cannot be directly compared to the field scanline J4 one.
Table 5-4. Discontinuity set orientation, trace intensity and mean trace length measured at the Mount Seymour roadcut using field-based scanlines and remote sensing circular windows (Type 3).

<table>
<thead>
<tr>
<th>Scanline</th>
<th>Discontinuity set (n=)</th>
<th>Dip [°]</th>
<th>Dip direction [°]</th>
<th>Fisher K</th>
<th>Trace intensity (P10) [1/m]</th>
<th>Trace intensity (P21) [m/m²]</th>
<th>True mean trace length [m]</th>
<th>Measured mean trace length [m]</th>
<th>Scanline or window dip/dip direction [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1 (14)</td>
<td>74</td>
<td>299</td>
<td>124</td>
<td>3.45</td>
<td>2.77¹</td>
<td>n/a</td>
<td>2.36</td>
<td>60/130</td>
<td></td>
</tr>
<tr>
<td>J2 (34)</td>
<td>67</td>
<td>177</td>
<td>72</td>
<td>4</td>
<td>3.67¹</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>00/215</td>
</tr>
<tr>
<td>J3 (6)</td>
<td>41</td>
<td>23</td>
<td>81</td>
<td>1.08</td>
<td>1.06¹</td>
<td>2.36</td>
<td>2.36</td>
<td>35/210</td>
<td></td>
</tr>
<tr>
<td>J4 (6)</td>
<td>15</td>
<td>190</td>
<td>150</td>
<td>0.67</td>
<td>n/a</td>
<td>2.08</td>
<td>75/010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1 (51)</td>
<td>79</td>
<td>299</td>
<td>71</td>
<td>1.11²</td>
<td>0.71</td>
<td>1.88</td>
<td>2.68</td>
<td>74/137</td>
<td></td>
</tr>
<tr>
<td>J2 (42)</td>
<td>75</td>
<td>177</td>
<td>43</td>
<td>0.94²</td>
<td>0.46</td>
<td>1.42</td>
<td>1.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J3 (5)</td>
<td>33</td>
<td>17</td>
<td>98</td>
<td>0.26²</td>
<td>0.13</td>
<td>7.76</td>
<td>7.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bootstrap (84)</td>
<td>n/a</td>
<td>n/a</td>
<td>150</td>
<td>n/a</td>
<td>1.54</td>
<td>2.66</td>
<td>1.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1 (44)</td>
<td>75</td>
<td>301</td>
<td>100</td>
<td>1.66²</td>
<td>0.93</td>
<td>1.01</td>
<td>1.29</td>
<td>77/135</td>
<td></td>
</tr>
<tr>
<td>J2 (49)</td>
<td>76</td>
<td>178</td>
<td>50</td>
<td>0.85²</td>
<td>0.71</td>
<td>0.76</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J3 (12)</td>
<td>31</td>
<td>36</td>
<td>100</td>
<td>0.59²</td>
<td>0.36</td>
<td>1.83</td>
<td>2.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bootstrap (62)</td>
<td>n/a</td>
<td>n/a</td>
<td>300</td>
<td>n/a</td>
<td>0.57</td>
<td>0.47</td>
<td>0.87</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ measured for comparison based on virtual FracMan windows
² measured for comparison based on virtual FracMan scanlines
³ estimated using remote sensing topographic window and Mauldon et al. (2001) count method
⁴ measured as the average length/diameter of all discontinuities intersecting, transecting and contained in remote sensing circular windows
There are several possible explanations for the observed differences in both mean trace length and trace intensity estimation. First, as shown in Fig. 5-10, scanlines and windows due to accessibility cover slightly different sections of the road cut. Consequently, they may consider different structural “zones” or data samples, although no evidence of major structural domain variation has been observed. More importantly, the differences seem to be controlled by the sampling method and the relative influence of associated inherent sampling bias on the estimation of mean trace length and trace intensity.

Scanline mapping is highly sensitive to in plane length bias, because longer traces have a higher probability of intersecting the scanline than shorter ones (Priest, 2004). As a result, overestimation of trace length measurements should be expected. Although window mapping is also subject to in plane length bias (Zhang and Einstein, 2000), the significant number of short traces, contained within the sampling area will reduce the estimated value of mean trace length (Table 5-3 highlights that the “m” count is often significantly greater than the “n” count). As will be discussed in Section 5.5.2, this will influence the generated block parameters.

On the other hand, using window mapping, underestimation of fracture frequency is difficult to avoid, and the mapping of a large number of short traces requires special
care. This is illustrated in Table 5-4 and Fig. 5-9 where trace intensity is significantly lower using window mapping. Furthermore, the estimation of the frequency of discontinuity sets characterized by persistent and largely spaced fractures is critical using window mapping. Indeed, if the number of traces is not large enough, such as for J3, the Mauldon et al. (2001) count method may not be reliable. Yet, in the case of the Mount Seymour outcrop, Section 5.5.2 will show that the generation of discrete blocks is highly dependent on the presence of J3 discontinuities.

Differences in mean trace length and trace intensity are also expected because of the observation scale effect (Sturzenegger and Stead, 2009a) and truncation associated with the choice of a sampling level. The observation scale effect (or scale bias) results in a variation in the estimated discontinuity parameters, using varying ground resolutions. Sturzenegger and Stead (2009b) reported that observation scale effects on discontinuity persistence measurements include truncation of small discontinuities with respect to the ground resolution and overestimation of the length of extremely persistent features as a result of step-path geometries. Observation scale effects on discontinuity orientation measurements can include both orientation bias and shift in discontinuity orientation (Sturzenegger and Stead, 2009b).

Finally, it is important to emphasize that the geometry of the Mount Seymour outcrop limits the application of remote sensing windows to one single orientation, while an ideal situation would include the mapping of two or three faces normal to each other. Although the use of topographic windows should allow reduction in the orientation bias when the rock slope has sufficient relief, some occlusion zones cannot be avoided.
Figure 5-10. The Mount Seymour roadcut with the position of field-based scanlines (black bold lines) and remote sensing circular windows level 1 and 2.

5.5.2 Block size

Five FracMan models of the Mount Seymour road cut have been created, based on both field-based scanline and TLS point cloud measurements (Table 5-5). The results of the block fragmentation analyses are presented in Figs. 5-11 and 5-12, and illustrated in Fig. 5-13. The FracMan analyses assume fractures generated within a 5 x 5 x 5 metres rock mass cube.

| Table 5-5. FracMan models of the Mount Seymour road cut. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Sampling method** | **Model I** | **Model II** | **Model III** | **Model IV** | **Model V** |
| Field-based scanline | TLS Window Type 3 (level 1) | TLS Window Type 3 (level 2) |
| **Discontinuity shape** | Hexagonal | Hexagonal | Square | Hexagonal | Hexagonal |
Figure 5-11. Characterization of rock mass block parameters using fragmentation analyses on the five TLS and field scanline FracMan models of the Mount Seymour road cut. (a) Number of blocks, (b) mean block size, (c) total volume occupied by blocks.
Figure 5-12. Block volume distribution resulting from the FracMan fragmentation analyses on the five TLS and field scanline simulations of the Mount Seymour road cut.

Figure 5-13. FracMan blocks generated, illustrating the variation in block number and volume. (a) Model I, (b) Model III.

The results for the various FracMan models in Figs. 5-11 to 5-13 highlight the variation in block number, mean block size and total volume occupied by blocks. These
three block parameters reflect the amount and size of rock bridges in the rock mass, i.e., the amount of intact rock breakage required to create discrete blocks. A striking difference between field-based and TLS models is that remote sensing window data generate significantly fewer discrete blocks, representing a much lower percentage of the rock mass than field-based scanlines data.

In Section 5.5.1, the influence of the observation scale effect on both mean trace length and trace intensity has been highlighted, based on previous studies by the author, which compared field-based and remote sensing measurements. It was shown that remote sensing data provide lower trace intensity estimations, which will consequently influence simulated block parameters.

Three other parameters are shown to have an influence on block parameters. In Models I, II, III and V, the form of trace length distributions has been assumed to be negative exponential, because, as suggested in Section 5.3.3, it would account for truncation bias. For comparison, Model IV shows that a lognormal distribution results in slightly different block parameters (Fig. 5-11). Similarly, discontinuity shape has a significant influence on generated block parameters, as shown in Model III. Finally, Models II and IV illustrate the variation associated with the mapping level of detail.

Figure 5-12 illustrates the block size distributions for the five Fracman models. Models I, II, III and V present very similar distributions with a maximum block size of 1 m$^3$, although the percentage of blocks smaller than 0.2 m$^3$ ranges between 50 and 80%. The block size distribution of Model IV is slightly different with a maximum block size of 0.2 m$^3$.

5.5.3 Block shape

Block shape distributions for the Mount Seymour datasets obtained from both field-based scanline (Model I) and terrestrial laser scanner (Model III) are shown in Fig. 5-14, based on the classification developed by Kalenchuk et al. (2006). Both shape distributions range from cubic to elongated, with a significant number of platy-cubic blocks and a few of elongated-platy shape.
Figure 5-14. Block shape distribution for the Mount Seymour road cut. (a) Field-based scanline dataset (Model I), (b) TLS dataset (Model III). $\alpha$ and $\beta$ represent the block flatness and elongation, respectively.
5.5.4 Medium-range remote sensing discontinuity observations

A study of trace intensity determination using medium-range (300 – 1000 m) TLS/TDP 3D models is presented for two rock slopes at Bridal Veil Falls and Mt. Edith Cavell, in the Canadian Rocky Mountains (Fig. 5-15 and Table 5-6). The method of Mauldon et al. (2001) using remote sensing topographic circular windows of constant radius is applied to 3D models with varying ground resolutions. The intensity of the entire trace population, including several discontinuity sets, is measured.

Table 5-7 shows that, for all medium-range 3D models, trace intensity values are very low, ranging between 0.13 and 0.34 m/m², which is 2 to 12 times lower than the values measured at close-range, on the four road cuts in Table 5-3. In contrast, the trace intensity measured on the Mt. Edith Cavell rock slope at close-range (sampling window C in Table 5-7), is similar to the intensities measured on the road cuts in Table 5-3.

Clearly, the trace intensity values measured at medium-range are not representative of the actual discontinuity frequency of the rock slopes, and their incorporation into DFN models would provide unrealistic block size and shape parameters. The reason for this lack of trace measurements is related to occlusions and the observation scale, whose effects are amplified at medium-range.
Figure 5-15. Rock slopes, associated discontinuity orientations and sets measured using TLS/TDP 3D models. (a) Bridal Veil Falls, (b) Mount Edith Cavell. Window C is a 3 m diameter window located at the end of the black arrow.
Table 5-6. Bridal Veil Falls and Mount Edith Cavell rock slope characteristics (based on Sturzenegger and Stead, 2009b).

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
<th>Rock type</th>
<th>Age</th>
<th>Structure</th>
<th>Imaged area: height/length [m]</th>
<th>Average slope dip/dip direction [°]</th>
<th>Average Range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridal Veil Falls (Fig. 5-15a)</td>
<td>Highway 93, between Saskatchewan Crossing and Jasper, Alberta</td>
<td>Palliser Formation (Beach, 1943; Meijer Drees et al., 1993). Lower (Morro) Member: massive and resistant, cliff forming, grey and dark greyish brown mottled, dolomitic limestone. Upper (Costigan) Member: interbedded succession of dolostone, silty dolostone and fossiliferous limestone.</td>
<td>Upper Devonian</td>
<td>Steep anclinal rock slope, with overhanging blocks</td>
<td>65/145</td>
<td>87/191</td>
<td>430</td>
</tr>
<tr>
<td>Mount Edith Cavell (Fig. 5-15b)</td>
<td>20 km south of Jasper, Alberta</td>
<td>Gog Group (Aitken, 1968). Thick units of very fine and fine-grained sandstone and quartzite.</td>
<td>Lower Cambrian</td>
<td>Very brittle and intensively fractured rock; anclinal slope</td>
<td>160/240</td>
<td>72/053</td>
<td>550</td>
</tr>
</tbody>
</table>
Table 5-7. Remote sensing topographic windows at the Bridal Veil Falls and Mount Edith Cavell rock slopes (TDP=Terrestrial Digital Photogrammetry; TLS=Terrestrial Laser Scanning).

<table>
<thead>
<tr>
<th>Window ID</th>
<th>Location</th>
<th>Technique/f Range [m]</th>
<th>Ground point spacing [m]</th>
<th>Window radius [m]</th>
<th>“m” count</th>
<th>“n” count</th>
<th>Trace density ((P_{20})) [1/m]</th>
<th>Trace intensity ((P_{21})) [m/m²]</th>
<th>Mean Trace length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Bridal Falls TDP 50 mm</td>
<td>430</td>
<td>0.442</td>
<td>25</td>
<td>50</td>
<td>18</td>
<td>0.013</td>
<td>0.18</td>
<td>14.14</td>
</tr>
<tr>
<td>A</td>
<td>Bridal Falls TDP 200 mm</td>
<td>430</td>
<td>0.110</td>
<td>25</td>
<td>85</td>
<td>24</td>
<td>0.022</td>
<td>0.24</td>
<td>11.09</td>
</tr>
<tr>
<td>A</td>
<td>Bridal Falls TDP 400 mm</td>
<td>430</td>
<td>0.055</td>
<td>25</td>
<td>112</td>
<td>22</td>
<td>0.029</td>
<td>0.22</td>
<td>7.71</td>
</tr>
<tr>
<td>A</td>
<td>Bridal Falls TLS</td>
<td>430</td>
<td>0.321</td>
<td>25</td>
<td>47</td>
<td>15</td>
<td>0.012</td>
<td>0.15</td>
<td>12.53</td>
</tr>
<tr>
<td>A</td>
<td>Bridal Falls TLS</td>
<td>430</td>
<td>0.080</td>
<td>25</td>
<td>93</td>
<td>29</td>
<td>0.024</td>
<td>0.29</td>
<td>12.25</td>
</tr>
<tr>
<td>B</td>
<td>Bridal Falls TDP 50 mm</td>
<td>430</td>
<td>0.442</td>
<td>20</td>
<td>32</td>
<td>12</td>
<td>0.005</td>
<td>0.15</td>
<td>11.78</td>
</tr>
<tr>
<td>B</td>
<td>Bridal Falls TDP 200 mm</td>
<td>430</td>
<td>0.110</td>
<td>20</td>
<td>122</td>
<td>22</td>
<td>0.009</td>
<td>0.28</td>
<td>5.67</td>
</tr>
<tr>
<td>B</td>
<td>Bridal Falls TLS</td>
<td>430</td>
<td>0.321</td>
<td>20</td>
<td>49</td>
<td>11</td>
<td>0.004</td>
<td>0.14</td>
<td>7.05</td>
</tr>
<tr>
<td>B</td>
<td>Bridal Falls TLS</td>
<td>430</td>
<td>0.080</td>
<td>20</td>
<td>156</td>
<td>27</td>
<td>0.011</td>
<td>0.34</td>
<td>5.44</td>
</tr>
<tr>
<td>C</td>
<td>Mt. Cavell TDP 20 mm</td>
<td>6</td>
<td>0.015</td>
<td>1.5</td>
<td>42</td>
<td>14</td>
<td>2.971</td>
<td>2.33</td>
<td>0.79</td>
</tr>
<tr>
<td>D</td>
<td>Mt. Cavell TDP 50 mm</td>
<td>550</td>
<td>0.560</td>
<td>20</td>
<td>7</td>
<td>11</td>
<td>0.003</td>
<td>0.14</td>
<td>49.37</td>
</tr>
<tr>
<td>D</td>
<td>Mt. Cavell TDP 200 mm</td>
<td>550</td>
<td>0.140</td>
<td>20</td>
<td>30</td>
<td>14</td>
<td>0.012</td>
<td>0.18</td>
<td>14.66</td>
</tr>
<tr>
<td>D</td>
<td>Mt. Cavell TDP 400 mm</td>
<td>550</td>
<td>0.070</td>
<td>20</td>
<td>100</td>
<td>24</td>
<td>0.040</td>
<td>0.30</td>
<td>7.54</td>
</tr>
<tr>
<td>D</td>
<td>Mt. Cavell TLS</td>
<td>550</td>
<td>0.180</td>
<td>20</td>
<td>28</td>
<td>10</td>
<td>0.011</td>
<td>0.13</td>
<td>11.22</td>
</tr>
<tr>
<td>D</td>
<td>Mt. Cavell TLS</td>
<td>550</td>
<td>0.090</td>
<td>20</td>
<td>64</td>
<td>10</td>
<td>0.025</td>
<td>0.13</td>
<td>4.91</td>
</tr>
</tbody>
</table>
5.6 Discussion

The multiple forms of bias affecting the estimation of trace length and intensity has led to the creation of statistical sampling approaches, such as circular windows (Mauldon et al., 2001; Zhang and Einstein, 1998) or the semi-trace length sampling approach along scanline presented by Priest (1993 and 2004). Although very useful, the proposed estimators should be used with care as the initial assumptions required for their application are rarely entirely met. Consequently, in practice, mean trace length and intensity can only be approximated.

The incorporation of approximated mean trace length and intensity in DFN models requires further assumptions concerning trace length distribution and discontinuity shape. As a result, the generated DFN models and derived block size/shape distributions contain a significant uncertainty. It is also often unclear whether rock masses are expected to be formed mostly by discrete blocks or if there exists an initial significant amount of rock bridges, which may break over time and eventually create discrete blocks, under the influence of factors including stress, weathering, meteoric water and blast damage. The results in Section 5.5.2 suggest that actual discrete blocks represent only between as little as 1% and up to 14% of the rock mass. Table 5-8 summarizes the parameters contributing to the overall uncertainty associated with the estimation of mean trace length, trace intensity and block size/shape, using both field-based scanline and remote sensing window mapping.

With the increasing application of remote sensing techniques for rock mass discontinuity characterization, the author emphasize the need for improved quantification and understanding of this uncertainty, particularly considering the impact it may have on any subsequent designs using advanced numerical modeling. A comprehensive parametric study of the influence of each factor contributing to the uncertainty is clearly needed but beyond the scope of this study. Preliminary studies by Rogers et al. (2007), Elmo et al. (2007), Stead et al. (2009) and Rogers et al. (2009) have shown the influence of trace length, truncation bias and discontinuity intensity on block size distributions. Rogers et al. (2009) have shown that for a series of DFN models with increasing \( P_{32} \) values, the volume occupied by the blocks may increase from less than 10% of the total
volume to close to 100%. Furthermore, the conversion from rock bridge dominated to a more kinematically free rock mass appears to occur over a relatively small change in $P_{32}$.

Table 5-8. List of possible errors and resulting effects contributing to the overall uncertainty in the estimation of mean trace length, trace density and block size/shape.

<table>
<thead>
<tr>
<th>Analysis stage</th>
<th>Possible source of error</th>
<th>Possible resulting effect</th>
</tr>
</thead>
</table>
| Initial field observation | Rock mass characterization and fracture network understanding | ▪ Inappropriate discontinuity set definition  
▪ Under-evaluation of the importance of persistent fractures |
| Sampling and discontinuity parameter characterization | Field-based versus remote sensing-based | ▪ Sampling location limitation (field-based mapping)  
▪ Observation scale effect and occlusion (remote sensing mapping)  
▪ Orientation bias (field- and remote sensing-based mapping) |
| | Scanline versus window mapping | ▪ In plane length bias (scanline/window)  
▪ Under-estimation of short fracture frequency (window)  
▪ Under-estimation of persistent, widely-spaced discontinuity set frequency (window)  
▪ Censoring, truncation (scanline/window) |
| DFN model generation | Choice of a geometric/geologic model | ▪ Model geologically inappropriate  
▪ Influence of assumed discontinuity shape |
| | Statistical model | Inadequate form of discontinuity size or orientation distribution (present chapter; Lyman et al., 2008) |
| | Calibration process | Inaccurate input values if the calibration process is not achieved carefully |
| | Initial assumed percentage of rock bridges | Under-/over-estimation of block parameters |

Based on the results presented in this study and in consideration of the highlighted uncertainty, a significant degree of conservatism should be adopted when applying existing sampling methods using terrestrial remote sensing techniques. The author present a number of observations and recommendations.

i. The difference between field-based scanline and close-range remote sensing-based circular window estimations of mean trace length and intensity can result from a variety of parameters (see Sections 5.5.1, 5.5.2 and Table 5-8). With the available
technology, medium- and long-range remote sensing techniques cannot be used to reliably estimate mean trace length and intensity, and consequently for generation of DFN models. Sturzenegger and Stead (2009b), however, showed that these techniques can provide reliable information about discontinuity position, orientation and persistence suitable for kinematic analysis and numerical modeling, providing users consider possible observation scale effects.

ii. It is the author’s opinion that the data provided by terrestrial remote sensing techniques should be optimized. Consequently, as mentioned in Sturzenegger and Stead (2009a), remote sensing sampling windows should be used instead of remote sensing scanlines in order to ensure incorporation of measurements distributed over the entire rock exposure. Using topographic circular windows is another way to optimize remote sensing data and prevent loss of discontinuity measurements. It should be noted that topographic windows with significant relief may, however, not be practical, because of an excessive increase in the window area to be mapped. In such a situation, it is recommended to use multiple low relief windows. In this study, the maximum window relief amplitude ranges from 16 to 35% of the window diameter, except for SC3 (41%).

iii. It is proposed that the negative exponential trace length distribution is the most realistic, as it implicitly accounts for truncation bias. This assumption is based on the observation that the number of non-persistent discontinuities increases with increasing resolution, as reported by Ortega et al. (2006) and Sturzenegger and Stead (2009b).

iv. It should be realized that the method of Mauldon et al. (2001) is a statistical approach based on intersection and endpoint counts, and not on actual measurements of trace length. Consequently, in order to obtain reliable results, it should be applied a number of times on various exposures. However, in practice, there is a limited number of available locations and consequently, the estimated trace length should be considered critically. In order to obtain more confidence, it is suggested that the average diameter of all discontinuities intersecting, transecting and contained in circular windows be measured, in addition to the previous method of estimation. This allows consideration
of a range of mean trace length values as shown in Table 5-4 (between the “true” and “measured” mean trace length).

v. Special care should be given to persistent and widely-spaced joint sets or persistent individual discontinuities, because their presence has a major influence on the nature of fracture networks and consequently the size/shape of discrete blocks. In some cases, statistical sampling/generation processes may not be adequate to quantify/locate them accurately. Consequently, the geometry of such features should be verified visually when generating DFN models and, if required, they should be located deterministically.

5.7 Conclusion

This chapter presents an example of DFN model generation using discontinuity parameters measured by terrestrial remote sensing. This procedure is expected to become an increasingly important resource in the generation of advanced numerical models for slope stability analysis, such as FracMan rock wedge analysis, Elfen and Slope Model (e.g. Elmo and Stead, 2009; Elmo et al., 2009; Cundall and Damjanac, 2009), allowing the simulation of rock mass failure using realistic fracture networks. In addition, as rock slope modeling codes incorporate synthetic rock mass approaches (Mas Ivars et al., 2008), it is important that the users of remote sensing technologies are fully conversant with their limitations and advantages in the production of discrete fracture networks.

A preliminary methodology using topographic windows and DFN models has been developed and evaluated on six rock slopes, at various measurement ranges. Similar studies should be applied to a greater number of outcrops in varied rock types in order to increase confidence and allow improvements in the methodology. While remote sensing provides suitable data on discontinuity sets orientation and persistence at all scales, caution is needed in the measurement of trace intensity and block size. Remote sensing techniques should be used as an additional tool to complement conventional field mapping. In order to provide “true 3D” characterization of rock masses, remote sensing such as LiDAR and digital photogrammetry should also be used along side geophysics and borehole measurements.
The author also recommend further research to develop procedures to (semi-) automatically construct remote sensing windows on TLS/TDP 3D models. If remote sensing techniques are to become practical and reliable tools for DFN production, it is considered essential that they provide accurate and rapid measurements of discontinuity geometric parameters. Geologists and geological engineers should be able to focus on the manual delineation/observation of rock slope 3D models, including the definition of discontinuity sets and potential failure mechanisms. Computer-based algorithms should then be able to (semi-)automatically and rapidly process the digitally mapped discontinuities and extract parameters such as position, orientation, persistence, frequency and roughness.

5.8 Acknowledgments

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CHAPTER 6
INCORPORATION OF TERRESTRIAL DIGITAL PHOTOGRAMMETRY INTO THE INVESTIGATION OF THE PALLISER ROCKSLIDE

A modified version of the following chapter will be submitted as:

Sturzenegger, M., Stead. Incorporation of terrestrial digital photogrammetry into the investigation of the Palliser Rockslide. To be submitted.

6.1 Abstract

This chapter presents the results of an investigation of the prehistoric Palliser Rockslide, Rocky Mountains, Canada. Conventional aerial photograph interpretation and field mapping are complemented by terrestrial digital photogrammetry. These techniques allow quantification of the rockslide debris volume and reconstruction of the pre-slide topography. It has been estimated that the volume of rock involved in the most recent large rockslide ranges between 5 and 8 Mm$^3$. Terrestrial digital photogrammetry is also optimal for the characterization of the failure surface morphology, which can be subdivided into four types of step-path geometry comprising both pre-existing discontinuities and intact rock fractures. Incorporation of this data into various rock slope stability numerical modelling methods highlights a complex failure mechanism, which includes sliding along a large scale curved failure surface, intact rock bridge fracturing and lateral confinement. A preliminary quantification of the stabilizing effect of intact rock bridges, in terms of apparent cohesion (0.37 MPa) or cumulative length of intact rock segments (2% of the failure surface), is proposed.

6.2 Introduction

The morphology of rock slopes in the Rocky Mountains is predominantly controlled by penetrative bedding planes. Cruden (2000) characterizes slopes as cataclinal, when bedding planes dip in the same direction as the slope and anaclinal,
when they dip in a direction opposite to the slope. Cataclinal slopes can be further divided into overdip, underdip and dip slopes, when they are steeper, less steep or parallel to the dip of bedding planes, respectively.

Dip slope rockslides are widespread in the Rocky Mountains, where slope angles are close to the bedding plane dip angle (Cruden, 1975). The Palliser Rockslide, located in the Kananaskis Country, Alberta, is a typical example. Rockslides and rock avalanches are also common near geological contacts where resistant, usually massive cliff-forming carbonate units or thick, resistant clastic units overlie recessive clastics. Such conditions result from major overthrust faulting which superposes Paleozoic or Proterozoic carbonate units upon recessive clastics (Jackson, 2002). Slope movement across bedding planes, on anacinal slopes, are usually of smaller magnitude. They include toppling on bedding planes and sliding along daylighting cross or sheeting joints, and rock falls (Hu and Cruden, 1992; McAffee and Cruden, 1996; Gardner, 1983).

Landsliding has been shown to be a common and widespread geologic hazard in the Kananaskis area (Jackson, 2002). Cruden and Eaton (1987) mapped 228 post-glaciation slope movements whose debris cover areas larger than 5000 m$^2$. The majority of rockslide avalanches occur along bedding planes, on overdip slopes, where gravitational forces exceed the frictional forces resisting motion (Cruden, 1985; Cruden and Hu, 1993). Such a mechanism can also occur on dip slopes, where the base of the slope has been undercut by natural/glacial erosion, resulting in an overdip slope at the toe.

In a simple model of a sliding block on an inclined plane, failure occurs when the driving forces along the bedding plane exceed the frictional and cohesive resistance. Cruden (1985) argued that inclined penetrative bedding planes will normally be at the residual friction angle, because the folding that tilted the discontinuities from their originally horizontal orientation was accompanied by flexural slip, which reduced the peak frictional resistance and cohesion along the slip surface. Cruden (1975) proposed that the main cohesive force along bedding planes is provided by rock bridges. Their progressive destruction is caused by factors, including freeze-thaw mechanisms along the lateral and rear release surfaces, groundwater circulation at depth, progressive
gravitational displacements, earthquakes, damage due to glacial retreat and stress concentration induced by the height of the rock slope.

Failure of intact rock bridges may create a stepped failure surface morphology. In rock slope stability analyses, such as limit equilibrium or distinct element numerical methods, rock bridges can be implied using an apparent cohesion (Eberhardt et al., 2004; Karami et al., 2007) or incorporated explicitly (Jennings, 1970; Stead et al., 2006). The approach used by Einstein et al. (1983) and Moffit et al. (2007) involves determination of the “critical path” representing the combination of pre-existing discontinuities and intact rock fractures, having the lowest factor of safety and/or containing the lowest percentage of intact rock bridges.

In the case of the Palliser Rockslide, the critical path, i.e., the failure surface, is very well exposed, and presents a unique opportunity to study its stepped morphology. In addition, the recent development and application of high resolution terrestrial remote sensing technique on high mountain rock slopes (Sturzenegger and Stead, 2009b; Sturzenegger et al., 2009) provide appropriate tools for a detailed characterization of the failure surface. Consequently, in the present investigation, a combination of field and remote sensing techniques are used in a detailed characterization of the failure surface stepped morphology. Post-processing of both airborne and terrestrial 3D models is shown to provide high quality volume estimation and realistic pre-slide topography reconstruction. Finally, the incorporation of detailed 3D model data into numerical codes for stability analysis is also demonstrated.

6.3 Methodology

The investigation of the Palliser Rockslide was undertaken using a combination of laboratory, field and computer-based techniques, including air photograph interpretation, field mapping, terrestrial digital photogrammetry (TDP) and numerical modeling. Close- and long-range TDP surveys were achieved using a Canon EOS 30D digital camera with \( f = 20-400 \) mm lenses (Table 6-1) and the methodology described in Chapters 3 and 4 (Sturzenegger and Stead, 2009a and 2009b). 3D model generation and photogrammetric rock slope mapping were undertaken using the software 3DM CalibCam and 3DM

Table 6-1. **Ground resolution of both airborne and terrestrial 3D models.**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Focal length [mm]</th>
<th>Mean range [m]</th>
<th>Mean ground point spacing [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne photogrammetry</td>
<td>not available</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>TDP</td>
<td>20</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>TDP</td>
<td>50</td>
<td>3000</td>
<td>310</td>
</tr>
<tr>
<td>TDP</td>
<td>50</td>
<td>1000</td>
<td>103</td>
</tr>
<tr>
<td>TDP</td>
<td>200</td>
<td>1000</td>
<td>26</td>
</tr>
<tr>
<td>TDP</td>
<td>400</td>
<td>1000</td>
<td>13</td>
</tr>
</tbody>
</table>

Post-slide Digital Elevation Models (DEMs), representing the present topography, were obtained using airborne or terrestrial remote sensing techniques (Fig. 6-1a). Pre-slide DEMs were obtained by reshaping post-slide DEMs, i.e., by deleting points corresponding to slide debris and interpolating the pre-slide topography, based on geomorphologic observation (Fig. 6-1b). Calculation of slide debris volumes and thicknesses involved measurement of the difference between pre- and post-slide DEMs (Fig. 6-1c).

Reconstruction of the pre-slide topography of the mountain was achieved using a similar approach. Post-slide DEMs were used to project major structures (bedding planes, lateral/rear release surfaces), draw artificial points on these surfaces and incorporate the points into a DEM file. Simultaneously, points corresponding to the post-slide topography were deleted (Fig. 6-1d). A similar topographical reconstruction method, using intersection lines of interpolated structural features, has been presented by Oppikofer (2009). The main constraints on the reconstructed rock slope included a careful observation of the structure/morphology of the mountain and the volume of the debris, accounting for possible erosion and bulking. Common bulking percentages range between 20 and 30% (Brückl, 2001; Dunning et al., 2006; Poisel et al., 2008).
Figure 6-1. Calculation of rock slide debris volumes/thicknesses and reconstruction of the pre-slide topography. (a) Post-slide airborne DEM, (b) interpolated pre-slide airborne DEM, (c) difference between pre- and post-slide airborne DEMs giving the volume and thickness of the debris, (d) reconstruction of the pre-slide morphology of the mountain, constrained by the estimated debris volume (TDP DEM).
Slope stability analyses were undertaken using limit equilibrium (RocPlane: Rocscience Inc., 2008), finite element (Phase2: Rocscience Inc., 2008) and distinct elements methods, UDEC (Itasca, 2009a) and 3DEC (Itasca, 2009b). The RocPlane limit equilibrium planar failure analysis uses force equilibrium, i.e., the balance between resisting and driving forces, assuming a very simple rock slope geometry. Phase 2 allows the incorporation of in-situ stress and finite discontinuities along the failure surface to represent rock bridges explicitly. Finally, UDEC and 3DEC were used to study finite displacements along the failure surface. When assuming rigid blocks (3DEC), deformation and displacement can only occur along digitized discontinuities, whereas for the scenarios assuming deformable blocks (UDEC), the influence of stress concentrations along the failure surface can be accounted for.

### 6.4 Geographical and geological setting

The Palliser Rockslide is located in the Peter Lougheed Provincial Park, in the Kananaskis Country, approximately 130 km south west of Calgary (Alberta, Canada). The rockslide occurred on the south-western end of the Spray Mountains range, south of Mount Indefatigable, and on the north shore of the Upper Kananaskis Lake (Fig. 6-2). The present climatic conditions are characterized by a mean daily temperature ranging between -6.5 and 8.2°C and an annual precipitation of 558 mm. Almost half of the precipitation falls in the form of snow, and can cover the area from November to May (Environment Canada, 2009). Several glaciations occurred in the area during the Quaternary and sculptured the topography (Jackson, 1987).

The Palliser Rockslide occurred in the Front Ranges physiographic subprovince of the Rocky Mountains, a zone in which the dominant level of exposure is that of Devonian to Jurassic rocks of the paleo-North American continental shelf. The structure of the Front Ranges subprovince is characterized by the presence of a series of up to six main listric thrust slices that dip moderately to steeply west. These form characteristic rugged linear ranges of resistant Paleozoic carbonate rock separated by valleys carved in the weaker Mesozoic shales and sandstones (Price and Mountjoy, 1970). The steeply inclined resistant Paleozoic carbonate rocks form distinct topographic features due to
erosion of the overlying Mesozoic shaly units, and are represented as conspicuous linear commonly homoclinal mountain ranges (Price and Monger, 2000).

Figure 6-2. Location of the Peter Lougheed Provincial Park in the Canadian Rocky Mountains (a), and simplified structural map of the Palliser Rockslide neighbourhood (b).

The McConnell Thrust marks the boundary between the Front Ranges and the Foothills, which consist of a Lower Paleozoic to Middle Jurassic platformal succession overlain by a Late Jurassic to Paleocene foreland basin succession. The structure of the Foothills is dominated by listric thrust slices giving rise to a relatively subdued topography characterized by ridges that are formed by sandstones, and valleys, which are eroded in shales. The Front Ranges southwesterly boundary with the Eastern Main Ranges subprovince corresponds to segments of various overlapping thrust faults beyond which the dominant level of exposure is that of the pre-Devonian part of the continental shelf sequence (Price and Monger, 2000).

Mount Indefatigable and the Spray Mountain Range parallel the NW-SE trending Kananaskis River Valley, directly north of the Upper Kananaskis Lake (Fig. 6-2b) and are located just east of the Sarrail Creek Syncline. At the foot of the eastern flank of the Spray Mountain Range lie three imbrications of the Bourgeau Thrust (McMechan, 1998). The stratigraphic units are listed in Table 6-2 and illustrated in Fig. 6-3.
Table 6-2. Stratigraphic units present at the southern end of the Spray Mountain Range (based on McMechan, 1998).

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livingstone</td>
<td>Lower Carboniferous</td>
<td>Light grey, resistant, locally cherty skeletal lime grainstone and packstone, and dolomitized equivalents; local brown weathering, silty dolostone</td>
</tr>
</tbody>
</table>
| Banff            | Lower Carboniferous  | Upper unit: cherty lime wackestone, packstone and dolostone; dark, bedded chert with carbonate lenses; minor lime grainstone (upper part); brown weathering silty dolostone  
|                  |                      | Middle unit: interbedded chert, spicullite and spicular carbonate from a resistant unit at the base; overlain by recessive, black, siliceous shale, argillaceous carbonates, chert and minor siltstone locally  
|                  |                      | Lower unit: recessive, black shale interbedded with argillaceous to cherty spicular lime wackestone, with spicullite in the upper part |
| Exshaw           | Upper Devonian/Lower Carboniferous | Upper part: brown weathering, dolomitic and calcareous, commonly bioturbated siltstone  
|                  |                      | Lower part: rusty weathering, recessive black shale |
| Palliser         | Upper Devonian       | Upper unit: argillaceous, wavy bedded limestone, commonly cherty; cleaved in western exposures; subordinate thin, more resistant limestone interbeds  
|                  |                      | Lower unit: resistant massive weathering, burrow mottled dolomitic pelloidal limestone, and minor argillaceous limestone; commonly altered to a dark dolostone near the Bourgeau Thrust |
| Alexo            | Upper Devonian       | Dolomitic and calcareous sandstone and siltstone, silty carbonate, sandstone, siltstone and minor shale |
| Southesk         | Upper Devonian       | Light grey weathering, fine to coarse crystalline dolostone |
On the southwestern flank of the Spray Mountain Range, bedding generally dips steeply southwestward, flattening as it nears the hinge of the Sarrail Creek Syncline (Fig. 6-3). The Palliser Rockslide occurred along bedding planes on the south-western flank of Mount Indefatigable. The slide creates a curvilinear rupture surface, horizontal at the syncline hinge zone and dipping at 50° toward the top of the failure surface (Fig. 6-3). Cruden and Eaton (1987) reported evidence of flexural-slip in a zone of sheared rock between two beds and on a recently exposed bedding plane with calcite coating along the failure surface (Fig. 6-4c). The southwestern slopes of Mount Indefatigable, north of the slide area, are similar in structure to the pre-slide mass, however, increased resistance to sliding is present southwest of the syncline due to a rock “buttress”, where bedding planes dip northeastwards into the mountain (anaclinal) (Fig. 6-5a).

6.5 Field, terrestrial and airborne imagery-based characterization

6.5.1 Rockslide activity and volume

Jackson (1987) mapped the surficial geology of the southern end of the Spray Mountain Range as predominantly composed of rapidly wasting bedrock slopes overlain by colluvial veneer and colluvial blankets. Active erosional and depositional processes include debris flows, and rock and snow avalanches, resulting in a widespread bouldery landscape.
Aerial photograph interpretation shows that a large area of the hummocky deposit at the base of the south-western end of the Spray Mountain Range is covered with vegetation and trees, while another part comprises mostly unvegetated rocky debris (Fig. 6-4a). In addition, field observations reveal that blocks in the vegetated debris originated from the Livingstone Formation, while the non-vegetated part of the debris is composed of fissile blocks from the Upper Banff Formation. This information implies the occurrence of at least two major rockslides, with the oldest probably involving upper stratigraphical sections. The run-out distance of the older and younger rockslides are approximately 3 and 2 km, and their volume at least 20 and 5 Mm$^3$, respectively. The maximum estimated thickness of the younger rockslide is 32 metres.

Estimation of the volume and thickness of the younger debris has been based on an airborne DEM (Canadian Digital Elevation Data at a 1:50000 scale) (CCOG, 2008). The 20 m resolution of this DEM is too low to obtain a reliable estimation of the volume of the older debris. Further work should consider the acquisition of a higher resolution airborne LiDAR DEM in combination with data concerning debris deposited in the Upper Kananaskis Lake. Cruden and Eaton (1987) estimated a total volume of 90 Mm$^3$, but did not specify the presence of two distinct events. The volume measured in this study is significantly less than that reported previously.

Two smaller more recent debris deposits, A and B, were recognized at the base of the rock slope with volumes of 7900 and 740 m$^3$, respectively (Fig. 6-4b). The estimated sizes of the larger blocks present are 8 and 3.4 m$^3$, respectively. The scar of another small slide, C, involving 1350 m$^3$, can also be observed on the rock slope (Fig. 6-4b), evidence for relatively recent rockslide activity. Events A, B and C indicate that the failure surfaces of the two large rockslides have been at least partly eroded and that the south-western end of the mountain range is subject to rockslides on a relatively regular basis.
Figure 6-4. Rockslide debris. (a) Aerial photograph showing the hummocky texture of the two rockslide deposits, the older one being larger and covered with vegetation. The lateral limits of the older and younger debris are drawn with a dotted white line and a dashed black and white line, respectively. (b) Detail of the failure surface highlighting two small, relatively recent rockslide deposits (A and B). The white arrow shows the relatively recent fresh scar of another small event (C). (c) Calcite coating along the exposed scar.
6.5.2 **Structure of the landslide**

The failure surfaces of the rockslides follow several bedding planes in the recessive Upper Banff Formation, truncated in the south east and terminating against a large lateral cliff in the north west. A succession of bedding planes and lateral release surfaces forms a failure surface with both down-dip and a laterally stepped morphology (Fig. 6-5b and Fig. 6-11). In the upper part of the slope, persistent bedding planes daylight. The southwestern end of the Spray Mountain Range is a particularly favorable location for sliding, due to the absence of lateral confinement on the south east. Figure 6-6 shows evidence of groundwater circulation, including seepage and karstic features.

The contact between the Upper Banff and the competent Livingstone Formations is present along the lower part of the NW lateral cliff (Fig. 6-5c). The southeastern end of the Spray Mountain Range is characterized by the presence of three gullies following black-shale layers dipping between 40 and 50° to the southwest (Fig. 6-5c). At the southwestern end of the NW lateral cliff, the axial surface of the Sarrail Creek Syncline is expressed as a steep gully (Figs. 6-5a and 6-7). No fault has been observed in the gully, but evidence of water circulation and calcite recrystallization exist. The rock mass in the gully is highly fractured with a Geological Strength Index (GSI) ranging between 30 and 40. As mentioned previously, the north east dipping limb of the syncline forms a “buttress” to slope movement.

Scanline mapping has been undertaken at two locations along the base of the failure surface (Fig. 6-5c). At both locations, two orthogonal scanlines were carried out in order to limit orientation bias. The discontinuity sets identified include low to medium persistence (ISRM, 1978) bedding planes, S0, and three sets of very low persistence cross joints (J1, J2 and J3) (Tables 6-3 and 6-4; Figs. 6-8a and 6-8b). The cross joints are very closely spaced (ISRM, 1978), whereas bedding planes are extremely to very closely spaced, creating cubic to platy-cubic blocks (Table 6-4). Millimetre carbonate infill was observed on four bedding planes and three J1 joints along scanline 1.
Figure 6-5. The Palliser Rockslide. (a) Southwestern end of the NW lateral cliff illustrating the Sarrail Creek Syncline and the gully along its axial surface, (b) down-dip and laterally stepped morphology of the failure surface, (c) general view of the southern end of the Spray Mountain range showing the approximate limit of the landslide (dashed white line), locations of scanline 1 and 2, and the location of bedding roughness measurements.
Figure 6-6. Evidence of groundwater circulation on the Palliser Rockslide. (a) Seepage (full black arrows) and karstic features (dotted black arrows), (b) detail of a karstic feature, (c) close-up showing seepage along bedding planes and carbonate recrystallization.
Figure 6-7. Interpretation of the open, symmetrical, near-cylindrical Sarrail Creek Syncline geometry, based on 56 bedding planes measurements made on both limbs using the $f = 200$ mm photogrammetric 3D model (stereonet lower hemisphere, equal area projection).

Additional compass measurements obtained at various locations along the base of the failure and along the ridge of the mountain closely agree with orientation measurements made along scanlines 1 and 2. However, the dip of the bedding planes ranges between $24^\circ$ and $52^\circ$, along the base and top of the failure surface, respectively, because of large scale fold-related curvature (Fig. 6-8c). Discontinuity set J1 is ubiquitous. Sets J2 and J3 are distinct sets and at least one of them is present at a locality.

Figure 6-8d shows a stereonet obtained using the $f = 200$ mm photogrammetric 3D model, whose resolution limits practical measurements to discontinuities more persistent than about 2 m. The objective of 3D model mapping in this study was to investigate the morphology of the entire failure surface (see step-path types in Section 6.5.3), consequently a major effort was made to differentiate actual fracture surfaces from composite surfaces, composed of a combination of cross joints and intact rock fractures. Very high persistence bedding planes, high persistence J1 and J2 are clearly recognized on the stereonet, although the resolution and view angle of the 3D model makes it more difficult to map J1. Two additional distinct minor medium persistence sets, J1’ and J2’ were also observed when mapping the NW lateral cliff (Table 6-3).
Field estimation of bedding plane roughness/waviness (ISRM, 1978) varies between rough/undulating and smooth/planar at the locations of scanline 1 and 2, respectively. The $f = 200$ mm photogrammetric 3D model was also used to quantify bedding waviness, using the virtual compass and disc-clinometer method presented by Sturzenegger and Stead (2009a). Measurements in 25 areas, about 1.5-2 m in diameter, have been undertaken along two bedding planes (Fig. 6-5c) and the obtained roughness angle, $i$, was 4 and 5°, respectively.

![Discontinuity set orientation](image)

Figure 6-8. Discontinuity set orientation (stereonets lower hemisphere, equal area projection, first contour = 3%, interval = 2% per 1% area). Compass measurements along (a) scanline 1 and 2 (b), (c) bedding planes at the toe of the failure surface and along the ridge of the mountain, (d) discontinuities mapped on the $f = 200$ mm photogrammetric 3D model (entire landslide without the “buttress”), (e) discontinuities mapped on the “buttress” (southwestern limb of the Sarrail Creek Syncline) using the photogrammetric 3D model ($f = 200$ mm).

On the southwestern limb of the syncline, very high persistence bedding planes dip on average at 43° northeastwards (Fig. 6-8e). Two sets of high persistence cross joints have been recognized although the resolution and view angle of the 3D model
makes it more difficult to map JB2. Field observations of JB1 reveal medium to very high persistence wavy discontinuities (Fig. 6-9) (ISRM, 1978). It is worth noting that the geometry of the discontinuity sets in the “buttress” is very similar to the rest of the study area, the orientation of JB1 and S0’ being interchanged (Fig. 6-8e). The major difference is that the daylighting discontinuity set is JB1, which is less persistent than S0’ (Table 6-3) and may consequently influence the type of failure mechanism. Further study of the “buttress” area is recommended.

Figure 6-9. 15-20 metre persistence (along strike) wavy discontinuity (JB1) at the base of the “buttress” (see location on Fig. 6-5a). The tripod is 1 m high for scale.
Table 6-3. Discontinuity set geometry properties, measured at the base of the failure surface, along scanlines 1 and 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Discontinuity set</th>
<th>No. poles</th>
<th>Mean Dip [°]</th>
<th>Mean Dip direction [°]</th>
<th>Fisher K</th>
<th>Mean persistence [m]</th>
<th>Persistence range [m]</th>
<th>Mean Spacing [m]</th>
<th>Infill</th>
<th>Roughness /waviness</th>
<th>Block size and shape /GSI [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scanline 1</strong></td>
<td>Base of failure</td>
<td>S0</td>
<td>13</td>
<td>34</td>
<td>239</td>
<td>216</td>
<td>1.6</td>
<td>0.6-2.5</td>
<td>0.12</td>
<td>carbonate (4 planes)</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>surface</td>
<td>J1</td>
<td>22</td>
<td>55</td>
<td>59</td>
<td>228</td>
<td>0.9</td>
<td>0.1-3</td>
<td>0.48</td>
<td>carbonate (3 planes)</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J2</td>
<td>16</td>
<td>85</td>
<td>144</td>
<td>27</td>
<td>0.5</td>
<td>0.1-3</td>
<td>0.66</td>
<td>clean</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Scanline 2</strong></td>
<td>Base of failure</td>
<td>S0</td>
<td>13</td>
<td>30</td>
<td>246</td>
<td>223</td>
<td>7.4</td>
<td>0.5-30</td>
<td>0.32</td>
<td>clean</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>surface</td>
<td>J1</td>
<td>23</td>
<td>56</td>
<td>73</td>
<td>37</td>
<td>0.9</td>
<td>0.2-4</td>
<td>0.36</td>
<td>clean</td>
<td>cubic /planar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J3</td>
<td>19</td>
<td>86</td>
<td>172</td>
<td>58</td>
<td>0.8</td>
<td>0.2-2.5</td>
<td>0.40</td>
<td>clean</td>
<td>/55-65</td>
</tr>
<tr>
<td><strong>3D model, f = 200 mm</strong></td>
<td>Entire scar</td>
<td>S0</td>
<td>33</td>
<td>39</td>
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<td>67</td>
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<td>not available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J1</td>
<td>20</td>
<td>59</td>
<td>52</td>
<td>43</td>
<td>11.4</td>
<td>2.6-54.4</td>
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<td>not available</td>
<td>not available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>J1’</td>
<td>9</td>
<td>70</td>
<td>7</td>
<td>190</td>
<td>5.5</td>
<td>2.4-8.19</td>
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<td>not available</td>
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<tr>
<td></td>
<td></td>
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<td>69</td>
<td>82</td>
<td>138</td>
<td>217</td>
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<tr>
<td></td>
<td></td>
<td>J2’</td>
<td>6</td>
<td>62</td>
<td>146</td>
<td>46</td>
<td>7.7</td>
<td>3.24-10.3</td>
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<tr>
<td><strong>Buttress</strong></td>
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<td>S0’</td>
<td>23</td>
<td>47</td>
<td>77</td>
<td>44</td>
<td>21.7</td>
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<td>not available</td>
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<td></td>
<td></td>
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<td>20</td>
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<td>213</td>
<td>45</td>
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<td>2.0-30.4</td>
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<td>JB2</td>
<td>6</td>
<td>83</td>
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<td>6.8-17.5</td>
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6.5.3 Failure surface morphology and failure mechanism

From examination of the photogrammetric 3D model, step-paths observed have been subdivided into four main types (Table 6-4). A significant part of the failure surface follows bedding planes, whose observed persistence varies between low to extremely high (ISRM, 1978), but also includes a number of steps in both dip and stike directions, whose height ranges over several orders of magnitude (centimetres to about 35 m). This combination of bedding planes, and steps creates step-path type 1 (Figs. 6-10 and 6-11) and can be easily observed using a progressive increase in the resolution of photogrammetric 3D models (f = 50 to 400 mm). Five classes of step height have been tentatively defined using ISRM (1978) spacing ranges for bedding planes (Fig. 6-11). The steps are themselves composed of both cross joints and intact rock fractures.

Other observed stepped surfaces include a combination of J2 (and/or J3) and intact rock fractures (step-path type 2; Fig. 6-10); a combination of bedding planes, J1, J2 (and/or J3) and intact rock fractures (step-path type 3; Fig. 6-10); and a combination of J1’ and intact rock fractures (step-path type 4; Fig. 6-10). These various step-path types are summarized in Table 6-4. Step-path types 1, 2 and 3 are widespread while step-path type 4 has been observed exclusively along the NW lateral cliff (Fig. 6-12). It is interesting to remark that the combination of pre-existing discontinuities and intact rock fractures can be recognized at several observation scales.

<table>
<thead>
<tr>
<th>Step-path type</th>
<th>Description</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S0 + cm to 35 m high steps in both dip and strike directions (the steps are themselves composed of step-path types 2 and/or 3)</td>
<td>Fig. 6-10 and 6-11</td>
</tr>
<tr>
<td>2</td>
<td>J2 and/or J3 + intact rock fractures</td>
<td>Fig. 6-10</td>
</tr>
<tr>
<td>3</td>
<td>S0 + J1 + J2 and/or J3 + intact rock fractures</td>
<td>Fig. 6-10</td>
</tr>
<tr>
<td>4</td>
<td>J1’ + intact rock fractures</td>
<td>Fig. 6-10</td>
</tr>
</tbody>
</table>

Mapping of low to very low persistence discontinuity surfaces along step-path type 3, using close-range TDP shows that between 50 and 60% of the step surface follows pre-existing discontinuities, while the remaining 40 to 50% result from intact rock fractures. Due to the resolution of the photogrammetric model (mean ground point
spacing = 3 cm), this estimation does not account for the possible presence of microfractures, which may influence the total percentage of pre-existing fractures. Intact rock fractures were recognized as irregular, non-planar surfaces distinct from generally planar joints, and sometimes as fresh surfaces contrasting with weathered joint surfaces (Fig. 6-13).

The failure mechanism of the Palliser Rockslide is complex, the failure surface being curved and involving intact rock fractures (Fig. 6-11). Sliding occurs along step-path type 1 and the lateral release surfaces consist of step-path type 2, 3 and/or 4. In addition, it will be demonstrated in Section 6.6.2 that the most recent major rockslide event involved a wedge failure, associated with the presence of an oblique feature at the base of the failure surface.

A potential failure mechanism in the “buttress” area is planar sliding along daylighting JB1 discontinuities recorded as medium to very high persistence. These wavy discontinuities developed along a combination of pre-existing non-persistent joints and intact rock fractures, which suggests that they could be gravity-induced surfaces. Further mapping and analysis of the “buttress” area may provide a better understanding of the stability of this part of the slope. It should be noted that high persistence vertical gravity-induced cracks were also observed behind the ridge, parallel to the NW lateral cliff (i.e., NE-SW striking) (Fig. 6-12).
Figure 6-10. Step-path types.
Figure 6-11. Description of step-path type 1 with steps linking bedding planes along the failure surface. (a) $f = 50$ mm photogrammetric 3D model showing major steps (white transparent zones), second and third order steps (white and black arrows, respectively), (b) $f = 200$ mm model showing fourth order steps (dashed arrows), (c) $f = 400$ mm model showing minor steps (dotted arrows).
Figure 6-12. Low resolution \( f = 50 \text{ mm} \) photogrammetric 3D model of the entire landslide mapped in terms of step-path types. The two rotating arrows indicate the location of observed cracks behind the ridge of the NW lateral cliff.
Figure 6-13. Examples of intact rock fractures along the upper part of the NW lateral cliff (a) and at the location of scanline 1 (b and c) (see Fig. 6-5).
6.5.4 Reconstruction of the pre-slide topography

An attempt to recreate the pre-slide topography of Mount Indefatigable has been undertaken using the methodology presented in Section 6.3. Several scenarios have been tested until the reconstructed volume corresponded to the volume estimation presented in Section 6.5.1. Figure 6-14 illustrates these scenarios for the younger major rockslide. The most realistic reconstruction has a volume of 8 Mm$^3$. This volume is larger than the estimated volume of the debris (5 Mm$^3$), especially when bulking is considered, however, it is probable that part of the failed block is now located in the adjacent Upper Kananaskis Lake (Fig. 6-4a) and that a significant amount of the blocky debris was deposited along the path of the slide and consequently was not accounted for in the volume estimation.

The reconstruction of the mountain morphology prior to the older rockslide is difficult to accomplish due to the large uncertainty associated with the debris volume estimations. It is probable that with a high resolution airborne LiDAR DEM and data concerning the upper Kananaskis Lake bathymetry, reliable measurements could be achieved.
Figure 6-14. Reconstruction of the pre-slide morphology of the mountain. Reconstruction (d) corresponds the closest to the estimated 5 Mm$^3$ debris volume.
6.6 Numerical modelling

The objective of this numerical modelling chapter is to demonstrate how incorporation of terrestrial remote sensing data into numerical models can be used to simulate a complex failure mechanism involving sliding along a large scale curved failure surface, intact rock bridge fracturing and lateral confinement. Modelling focuses primarily on the most recent rockslide. Morphologic and structural measurements of the failure surface have been provided by photogrammetric 3D models (Fig. 6-15 and Table 6-5) and the reconstructed pre-slide rock mass volume (area in 2D) used as a constraint for the generation of numerical models (Tables 6-6 and 6-7).

Rock mass, intact rock and discontinuity strength properties for the Upper Banff Formation have been estimated in RocLab, using the generalized Hoek-Brown failure criterion (Rocscience Inc., 2008), and discontinuity normal/shear stiffness assumed based on Kulhawy (1975). A Geological Strength Index (GSI) of 60 (Hoek and Brown, 1997; Hoek et al., 2002) and an average roughness angle of 5º, have been measured in the field and on photogrammetric 3D models (Section 6.5.2). Basic friction angles of the limestone bedding planes on Mount Indefatigable is 25º (Eaton, 1986), consequently the initial value of friction angle used in the modelling is 30º (basic friction angle + i).

Along the cross section of the failure surface, a second order step (Fig. 6-15) represents 0.9% of the total length of the profile. In addition, since 40-50% of the steps consist of intact rock fractures (see Section 6.5.3), an initial estimation of the percentage of rock bridges along the profile is 0.45%. The total percentage of rock bridges along the profile, including third order to minor steps, will be back-calculated in Section 6.6.1. In 3D, considering the surface of the failure surface for the 3DEC models, major and second-order steps (Fig. 6-15) represent 7% of the area, which results in an initial estimation of rock bridge percentage of 3.5%. For the 3DEC models, the topography at the southern end of the Spray Mountain Range has been simplified and the scar of the rock slide delineated using three surfaces S1, S2 and S3 (Table 6-5 and Fig. 6-15).
Table 6-5. Main surfaces of the younger major rockslide scar.

<table>
<thead>
<tr>
<th>Surface name</th>
<th>Dip [°]</th>
<th>Dip direction [°]</th>
<th>Morphological expression</th>
<th>Rock bridge [%]</th>
<th>Step-path type</th>
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<tr>
<td>S1</td>
<td>43</td>
<td>237</td>
<td>Bedding plane surface</td>
<td>3.5</td>
<td>Step-path type 1</td>
</tr>
<tr>
<td>S2</td>
<td>89</td>
<td>149</td>
<td>NW lateral cliff</td>
<td>40-50</td>
<td>Step-path type 2</td>
</tr>
<tr>
<td>S3</td>
<td>66</td>
<td>138</td>
<td>Oblique basal feature</td>
<td>40-50</td>
<td>Step-path type 3</td>
</tr>
</tbody>
</table>

Figure 6-15. Photogrammetric 3D model of the Palliser Rockslide, highlighting the failure surface of the most recent major rockslide in light grey.

6.6.1 2D modelling

As an initial stage in quantifying the influence of intact rock bridges, a simple limit equilibrium analysis of planar failure using RocPlane (Rocscience Inc., 2008) shows that the rock slope is at limit equilibrium with an apparent cohesion of 0.26 MPa (Table 6-6). A similar model with a straight failure surface (Fig. 6-16a) and incorporating in-situ stress (k=1) has been created in UDEC (Itasca, 2009a) (Scenario 1), which infers a similar cohesion value (0.24 MPa).
The second stage is to incorporate the large scale curvature of the failure surface in the slope failure analysis. UDEC Scenario 2 has the same parameters as Scenario 1 (Table 6-6), except that the actual topography of the curved failure surface is used (Fig. 6-16b). The required cohesion for stability is 0.37 MPa, which suggests that the large scale curvature has a significant destabilizing effect on the Palliser Rockslide.

![Image of UDEC modelling of the Palliser Rockslide](image)

**Figure 6-16.** UDEC modelling of the Palliser Rockslide. (a) Scenario 1 with a straight failure surface, (b) Scenario 2 with a curved failure surface (profile from the $f = 200$ mm photogrammetric 3D model), (c) Scenario 3 showing a detail of the main step along the curved failure surface and an explicit representation of two rock bridges, which were assigned intact rock strength properties.

As illustrated in the Phase2 model (Fig. 6-17), considering the 600 m high rock slope at the Palliser Rockslide and the presence of closely spaced bedding planes, sufficient tensile stress concentrations could be induced to break intact rock bridges and shape the stepped morphology of the failure surface. In the Phase2 finite element model (Rocscience Inc., 2008), in order to simulate intact rock fracturing of rock bridges, a small window at the location of the second-order step has been assigned intact rock strength properties using an elasto-plastic Mohr Coulomb constitutive model, whereas for
the rest of the slope elastic rock mass properties have been used (Table 6-6). This is undertaken to demonstrate in a simple manner the potential role of intact rock bridges in stability.

Figure 6-17. Phase2 finite element model illustrating the deviatoric stress distribution within the Palliser Rockslide and the yielded elements/joints at the location of a second-order step. Elements fracturing in tension are displayed with a red circle.

The assumed model configuration using intact rock strength properties within a small window is based on the evidence of intact rock fractures in addition to failure along pre-existing bedding planes and cross joints (Figs. 6-10 and 6-11). Based on field evidence, cross joint friction angle is 35° and no cohesion is assumed. Figure 6-17 clearly
illustrates how the failure surface may propagate between bedding planes, through intact rock bridges and along a pre-existing cross joint. It also shows zones of intact rock yielding at the tips of other pre-existing cross joints. The Phase2 model represents a potential snapshot in time just after failure has propagated through the step, the upper bedding plane having not yielded as far as the top of the slide yet (Fig. 6.17). It is assumed that the 3 MPa of apparent cohesion (Table 6-6) would have then decreased over time until complete failure occurred.

UDEC Scenario 3 expands upon the previous Phase2 analysis and represents intact rock bridges along steps of the cross section by attributing intact rock strength properties to segments of the profile (Fig. 6-16c), while assigning $\phi=30^\circ$ and apparent cohesion to the rest of the failure surface. This UDEC analysis shows that two 2.2 m long intact rock bridge segments along the second order step (Fig. 6-15) do not provide enough additional strength to stabilize the rock slope and that a further 0.36 MPa of apparent cohesion along the failure surface is necessary to prevent sliding. However, if the cumulative length of intact rock bridge segments is increased to 15 m, i.e., approximately 2% of the failure surface, the slope is stable. It is suggested that this percentage can be reached with the cumulative contribution of a larger number of third order to minor steps along the failure surface (Fig. 6-11).

The presented 2D numerical modelling study provides a quantification of the strength mobilized in rock bridges either as an apparent cohesion of 0.37 MPa or as a cumulative length of discrete segments of 15 m, i.e., approximately 2% of the failure surface. These figures should be considered as preliminary results, since a number of intact rock and rock mass parameters have been estimated using RocLab and are not based on laboratory testing of field samples. In addition, for simplicity and due to data uncertainty, neither groundwater nor earthquake acceleration have been accounted for.
Table 6-6. Parameters used for RocPlane, UDEC and Phase2 numerical modeling.

<table>
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<td>Slope angle [°]</td>
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<td>Based on post-slide photogrammetric 3D model profile</td>
<td>Based on post-slide photogrammetric 3D model profile</td>
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* This cohesion value does not represent the value at limit equilibrium, as explained in the text.

6.6.2 3D modelling

Two scenarios have been modelled with the three-dimensional distinct element code (3DEC) (Itasca, 2009b) in order to study the kinematic influence of lateral release surfaces on the stability of the rock slope. For this purpose, a rigid block assumption is
justified. However, the back-analysed strength values should be considered as preliminary and used with caution, as the stress induced within the rock mass by the 600 m high slope is not considered. The integration of intact rock bridges in this preliminary analysis was limited to the use of apparent cohesion along discontinuities.

The 3DEC Scenario 1 model assumes only surfaces S1 and S2 to investigate the influence of the lateral release surface S2 on the stability of the slope. This model shows that the stabilizing effect of the shear strength along S2 is negligible. Indeed, Scenario 1a, with no strength along S2, is stable (Table 6-7); while Scenario 1b, with a slight decrease in the apparent cohesion of S1, is unstable even with intact rock strength properties assumed along S2 (Table 6-7). Figure 6-18a shows that as soon as the sliding block moves, a small aperture is created along S2 and shear strength is no longer mobilized. The wedging effect of S2 being negligible, the mechanism can thus be considered as a “pseudo” planar sliding mechanism, with S2 acting as a lateral release surface. This result is not unexpected as kinematically, applying the Hocking’s test (Hoek and Bray, 1981), the S1 dip direction lies at the edge of the area defined by the slope dip direction and the line of intersection between S1 and S2 (Fig. 6-19a).

The 3DEC Scenario 2 model considers S3 in addition to S1 and S2. Scenario 2a is stable with an apparent cohesion of 0.7 MPa along S1 (Table 6-7). Scenario 2b is also stable with an apparent cohesion of 0.6 MPa and a slight increase of S3 friction angle (3°) illustrating the significant contribution of S3 to the stabilization of the sliding block (Table 6-7). Figure 6-18b demonstrates that the instability mechanism is a wedge failure. The Hocking’s test again confirms this behaviour, the S1 dip direction lying outside of the very small area defined by the slope dip direction and the line of intersection between S1 and S3 (Fig. 6-19b).
Figure 6-18. 3DEC models of the Palliser Rockslide showing the dark blue sliding block following the direction of the white arrow. (a) Scenario 1 with S1 and S2; a small aperture develops and the shear strength available along S2 is no longer mobilized to stabilize the sliding block, (b) Scenario 2 with S1, S2 and S3 displaying a wedge failure mechanism.

Figure 6-19. Hocking’s test applied to the wedges formed by (a) S1 and S2 (3DEC Scenario 1), (b) S1 and S3 (3DEC Scenario 2) (stereonet, lower hemisphere, equal area projection).
Table 6-7. Parameters used for 3DEC numerical modeling.

<table>
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<tr>
<th></th>
<th>3DEC Scenario 1</th>
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<td>Slope height [m]</td>
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<td></td>
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<td>b. 30</td>
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<td></td>
<td></td>
<td>b. 43 (S2)</td>
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6.7 Discussion

The prehistoric Palliser Rockslide, which occurred at the southern end of the Spray Mountain Range, in the Kananaskis Country, has been documented by Cruden and Eaton (1987), in a preliminary investigation. The present study provides further analyses of its activity, volume and failure surface morphology, using long-range terrestrial digital photogrammetry in addition to traditional aerial photographs and field mapping. Preliminary numerical modeling of the rockslide illustrates a complex failure mechanism,
including sliding along a large scale curved failure surface, intact rock bridge fracturing and lateral confinement.

The present study reveals that two major rockslides occurred, the first being much larger and older. More recent minor slides also suggest that mass wasting is an active process. The volume of these minor events could be accurately estimated using the photogrammetric 3D models. A significant uncertainty, however, remains concerning the volume of the younger major rockslide because of the unknown amount of debris distributed along the trajectory of the slide and which may be located beneath the Upper Kananaskis Lake. Finally, the volume estimation for the larger older rockslide is preliminary, as the available airborne DEM resolution is too low, nevertheless it appears that the measured volume is significantly less than that estimated by Cruden and Eaton (1987).

A reconstruction of the pre-slide topography of the mountain has been presented based on the debris volume estimation and morphologic observations. It is demonstrated that photogrammetric 3D models in combination with point cloud processing software (Polyworks) are particularly well-suited to such reconstructions. It must be emphasized that such reconstruction should be attempted carefully, as it depends on a large number of uncertain parameters, including debris volume, bulking percentage and accurate pre-slide location of the fallen rock mass. Long-range terrestrial digital photogrammetry is also well adapted for the characterization of the stepped geometry of the failure surface. Four types of step-path geometry have been observed along the scar of the Palliser Rockslide, types 2, 3 and 4 having already been described in Chapter 4 (Sturzenegger and Stead, 2009b) at other locations in the Canadian Rocky Mountains. In addition, a similar type of rockslide stepped failure surface (step-path type 1), although in a very different geological context, has been described by Oppikofer (2009).

Both complex planar sliding and wedge failure mechanisms have been observed and simulated. “Pseudo” planar sliding occurs along ubiquitous bedding planes, lateral release being provided by S2 surfaces. Two-dimensional numerical modeling suggests that the large scale curvature of the failure surface significantly influences the stability of the Palliser Rockslide. In the case of the younger major rockslide, another lateral
discontinuity surface (S3) creates a wedge with the bedding plane surface (S1) and consequently, the failure mechanism is distinctly three-dimensional. It can be expected that, depending on the presence of S3 surfaces, “pseudo” planar sliding or wedge failure could have occurred in the past and may occur in the future. As indicated previously, sliding is an active process at the southern end of the Spray Mountain Range.

A preliminary quantification of the stabilizing effect of intact rock bridges, in terms of apparent cohesion (0.37 MPa) or cumulative length of intact rock segments (2% of the failure surface) is proposed. This percentage is lower than proposed by Moffit et al. (2007) and Vyazmensky (2008), who suggest that a rock bridge percentage ranging from 8 to 15% of failure surfaces is required for stable conditions. However, the obtained percentage agrees with that proposed by Frayssines and Hantz (2006), which ranges between 0.2 and 5% on observed rockfall scars. They suggest that the apparent cohesion is proportional to both the percentage of rock bridges and the thickness of an unstable block. It is highly probable that the percentage of rock bridges required for stability is site specific and dependent upon both the geological structure and rock mass conditions in addition to other site related parameters.

Frayssines and Hantz (2006) also highlight two possible modes of intact rock bridge fracturing: tensile mode involving rear opening (release) surfaces and shear mode on translational sliding surfaces. At the Palliser Rockslide, shear mode also likely occurred along lateral release surfaces such as S2 and S3. This implies that the 2D UDEC-based quantification of intact rock bridges is limited, components of the fracturing being expected to occur along lateral surfaces under a shear mode. Consequently, a more accurate quantification of rock bridges would involve using a 3D approach, such as 3DEC.

The level of detail provided by terrestrial remote sensing techniques concerning the rockslide volume, both the pre-slide and post-slide topography, and the step-path geometry, is very useful for realistic modelling of the complex failure mechanism present at the Palliser Rockslide. Incorporation of photogrammetric 3D model data into a variety of numerical methods, from simple 2D limit equilibrium analysis using RocPlane, to 3D distinct elements analysis using 3DEC (Table 6-8) has been demonstrated. The author
suggest that realistic modelling of large landslides with complex failure mechanisms should fully use the benefits provided by terrestrial remote sensing techniques. Further work should consider using complex numerical models (Wang et al., 2003; Stead et al., 2006; Alzo’ubi, 2009; Cundall and Damjanac, 2009) allowing for an explicit simulation of intact rock fracturing through intact rock bridges.

Table 6-8. Level of topographic and morphologic detail, provided by terrestrial remote sensing techniques and incorporated into different numerical modelling methods.

<table>
<thead>
<tr>
<th></th>
<th>RocPlane</th>
<th>UDEC rigid/deformable blocks</th>
<th>Phase2</th>
<th>3DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>2D</td>
<td>2D</td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Mountain topography</td>
<td>no (straight line only)</td>
<td>yes</td>
<td>yes</td>
<td>possible (Simulation Works, 2008; Van Zeyl, 2009)</td>
</tr>
<tr>
<td>In-situ stress</td>
<td>no</td>
<td>no/yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Failure surface topography</td>
<td>no (straight line only)</td>
<td>yes</td>
<td>yes</td>
<td>possible (Simulation Works, 2008)</td>
</tr>
<tr>
<td>Rock bridges</td>
<td>implicit: apparent cohesion</td>
<td>implicit: apparent cohesion or segments with intact rock strength</td>
<td>explicit</td>
<td>implicit: apparent cohesion (future work required to incorporate areal segments with intact rock strength; 3DEC Voronoi under development)</td>
</tr>
</tbody>
</table>

6.8 Conclusion

The author believe that detailed characterization of failure surface geometry should be undertaken at large landslides wherever possible in order to create a major database of step-path geometries. Reported rockslides whose failure surface follows, at least partly, bedding planes include the Frank Slide (Cruden and Krahn, 1973; Langenberg et al., 2006), the Avalanche Lake Rock Avalanche (Evans et al., 1994) and several other rockslides in the Canadian Rocky Mountains (Cruden, 1975). Future incorporation of remote sensing details into advanced numerical models will improve our understanding of complex failure mechanisms.
Along the southwestern side of the Spray Mountain Range, on the southwestern limb of the Sarrail Creek Syncline, which defines the “buttress”, a different complex failure mechanism is expected. At this location, bedding planes dip into the slope, preventing sliding along them. However, irregular persistent daylighting fractures have been observed (Fig. 6-9). It is possible that these discontinuities represent gravity-induced features, developing through a combination of pre-existing cross joints and intact rock bridges. Further study should include the characterization of the structures in the “buttress” and the analysis of its stability. Future work at the Palliser Rockslide should also include dating of the rockslide debris and a more accurate quantification of the debris volume. An airborne LiDAR DEM together with lake bathymetry would help in more accurate volume/depth estimation and revised volumes for both major rockslide deposits.

6.9 Acknowledgments

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6.10 Reference list


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CHAPTER 7
DISCUSSION AND CONCLUSION

This discussion summarizes the contributions of this research; the first section presents an evaluation of terrestrial remote sensing techniques for discontinuity characterization, while the second section discusses the methodology developed in this research. This is intended to represent a first step towards a standardization of terrestrial remote sensing techniques in rock slope engineering.

7.1 Benefits of terrestrial remote sensing techniques for discontinuity characterization

The literature review presented in Section 1.3.6 highlights a number of advantages concerning the use of terrestrial digital remote sensing technique for discontinuity characterization. These include:

- the ability to sample extended windows that are not restricted to the base of an outcrop thereby providing more representative statistical samples,
- the ability to survey inaccessible steep and high rock faces,
- risk reduction for workers as the survey can be undertaken in a remote safe location protected from traffic and rock falls,
- the creation of a permanent record of the rock slope condition at a specific time,
- the possibility to measure discontinuity orientation when conventional compass clinometer readings are affected by magnetic orebodies.

The research presented in this thesis emphasizes additional important benefits provided by terrestrial remote sensing techniques, which represent specific assets in comparison to traditional sampling techniques.
7.1.1 Accurate quantification of discontinuity parameters

It has been demonstrated in Chapter 3 that terrestrial remote sensing techniques provide significant advantages in the quantification of discontinuity geometric parameters, with respect to traditional field mapping techniques. Discontinuity location in 3D coordinate systems can be easily undertaken. More representative measurements of discontinuity orientation can be obtained, by averaging entire fracture surfaces, as opposed to localized compass measurements. Similarly, primary roughness and curvature can be considered over larger surface exposures, instead of along short profiles.

Medium and higher persistence discontinuities can be accurately quantified, instead of roughly estimated at the outcrop. The quantification of persistent discontinuities is expected to be an important factor when considering large failures controlled by discontinuities, which extend over high rock slopes or multiple open-pit mine benches.

It is important to emphasize that other discontinuity parameters, such as aperture and infill, are less amenable to remote measurements, particularly when surveying rock slope from distances greater than 5 m. Similarly, the resolution of close-range field-based TLS/TDP 3D models normally does not allow measurement of secondary roughness. Consequently, a combination of both field and remote sensing techniques is considered essential to provide comprehensive discontinuity surveys.

7.1.2 Deterministic versus stochastic characterization of discontinuity networks

Discontinuity characterization is affected by uncertainty, which includes both limited measurements/exposures and natural variability of discontinuity parameters. Discontinuities are often considered as sets and their parameters defined stochastically using maximum likelihood values and associated confidence limits. It should be remembered that these limits are commonly based on assumptions regarding the underlying probability distributions of the parameters and that the sample size should not be significantly less than the population (Lyman et al., 2008).

A lack of measurements/exposures requires extrapolation of spatially available measurements to other inaccessible parts of fractured rock masses. For example, scanline
measurements achieved at the base of a rock exposure are extrapolated in the upper sections of rock cuts. While such an approach is adequate where fracture networks are regular, it may be inappropriate and non-conservative where networks are irregular or stability controlled by specific randomly located discontinuities. In such cases, terrestrial remote sensing techniques are extremely useful to provide deterministic measurements of potentially hazardous discontinuities. Such persistent discontinuities can be of paramount importance for rock slope stability or fluid flow circulation, but may be difficult to identify and/or under-represented along scanlines or boreholes (Marrett et al., 1999). In fact, by reducing the extent of extrapolation, terrestrial remote sensing techniques can provide more confidence in rock slope stability assessments and are recommended in order to maximize the deterministic information provided.

Terrestrial remote sensing techniques do not allow sub-surface measurements, and a combination of techniques, including borehole measurements will provide more complete datasets. This will be particularly important when considering larger rock exposures and deep-seated slope failures. The combination of terrestrial remote sensing techniques with geophysical imaging, such as ground penetrating radar (GPR), has been proposed by Deparis et al. (2008). This approach allows true 3D characterization of discontinuities, given that fractures are sufficiently opened and separated from each other (Deparis et al., 2007).

7.1.3 Extension of terrestrial remote sensing techniques to medium- and long-range

One of the main advantages of terrestrial remote sensing is to allow measurements of inaccessible exposures and thus to provide more representative samples of discontinuity networks. The extension of remote sensing techniques, and in particular terrestrial digital photogrammetry, to medium- (>300 m) and long-range (>1000 m) represents a significant advance. It can solve major access issues on both high mountain rock slopes and large open-pit mines.

An important issue when undertaking medium- and long-range remote sensing is a recognition of the survey planning requirements (registration, lens calibration, occlusion) and bias related to observation scale. It has been demonstrated in Chapter 4
that both discontinuity orientation and persistence can be measured at long-range, using a 
variety of resolutions (focal lengths), if the potential for observation scale effects is 
considered. Medium- and long-range terrestrial remote sensing provides detailed 
information for the assessment of failure mechanisms and slope stability.

Discontinuity frequency, on the other hand, cannot be adequately quantified at 
medium- and long-range, because of the truncation of low persistence discontinuities, 
which results in a significant underestimation of the number of discontinuities and hence 
block numbers (see Chapter 5).

7.1.4 Large landslide failure surface characterization and numerical modelling

It has been clearly shown in Chapter 6 that 3D remote sensing models allow 
detailed morphologic characterization of a large landslide failure surface, and in 
particular step-path geometries. TLS/TDP 3D models can also be used in the estimation 
of landslide debris volumes and to reconstruct the pre-slide topography. The 
incorporation of this information into numerical codes for rock slope stability analysis 
has been shown to provide optimal geometrical constraints and allow for realistic 
analyses of a complex failure mechanism. The Palliser Rockslide failure surface, being 
very well exposed, provides a particularly useful case study for a preliminary 
quantification of the strength and critical percentage of intact rock bridges in a major 
failure. It also demonstrates the constraint on rockslide analysis provided by long-range 
ground-based photogrammetry.

7.2 Towards a standardization of remote sensing-based discontinuity 
characterization

As remote sensing-based discontinuity characterization is being increasingly used 
by geologists and geological engineers, it is important to develop a standardized 
methodology that will insure appropriate application and high quality measurements. The 
following sections discuss the methodology developed in this research. Appendix 1 
provides practical details on the application of the methodology. Terrestrial remote 
sensing techniques should always be used in combination with conventional methods, 
including airborne photograph observations and field-based outcrop mapping.
7.2.1 Registration approach

Registration of TLS/TDP 3D models in a relative or global reference system is an important step in terrestrial remote sensing projects. The ability to set up a control point network is dependent on the accessibility of rock slopes and on rock fall hazard. Chapters 3, 4 and Appendix 2 propose and test a variety of possible registration approaches. It is intended that this will help practitioners decide on the optimal procedures and settings for specific projects.

It is shown that, in some cases, simple, fast and low-cost registration approaches can provide adequate measurements. At medium- and long-range, 3D model registration can become the most time consuming part of a survey and adequate and careful planning is of paramount importance.

7.2.2 Sampling bias definition

Similar to traditional field mapping, mapping on 3D remote sensing models is subject to sampling bias. Bias sources include orientation bias, truncation, censoring, length bias and f-bias. In Chapter 3, these concepts have been adapted for discontinuity characterization on 3D terrestrial remote sensing models, and their effects illustrated in Chapter 5.

The orientation bias associated with remote sensing techniques is complex. Sturzenegger et al. (2007) proposed to adapt the concept of a blind zone (Terzaghi, 1965) for remote sensing techniques and re-defined it as the locus of the poles of discontinuities parallel to the imaging system line-of-sight. Lato et al. (2010) further derived a weighting factor, for discontinuity sets whose normal are oblique to the line-of-sight, which should be applied when several rock exposure with various orientations are not available. It is recommended to use this bias correction with care considering the following limitations. Discontinuity sets biased on one side of the imaging system may not be the same as those biased on the other side (Lato et al., 2010). In addition, when mapping discontinuities manually (Section 7.2.3), discontinuity traces with significant relief can be measured, which minimizes orientation bias. Finally, bias correction can only be applied to discontinuity sets.
It has been highlighted in Chapter 3 that special care should be given to daylighting discontinuities, which are also sub-parallel to the imaging system line-of-sight. A slightly different approach to the orientation bias correction proposed by Lato et al. (2010) is the definition of a blind zone, i.e., a stereonet region where orientation bias is more likely to occur, and consequently which requires more care when mapping. A recent case study by Brideau et al. (2010) illustrates practical implications for rock slope stability analyses. In this example, a critical discontinuity set, sub-parallel to the camera line-of-sight, would have been overlooked if careful observation combined with field mapping had not been done (Figs. 7-1a, 7-1b and 7-1c). Figure 7-1d shows a preliminary adaptation of the blind zone concept (Terzaghi, 1965; Park and West, 2002) for remote sensing projects. The extent of blind zone should be defined using the same logic used by Lato et al. (2010), which considers a number of parameters, including camera/scanner line-of-sight and ground resolution. Indeed, it can be expected that the size of the blind zone will vary depending on the observation scale. Rock slope lateral extent is also an important factor, since biased discontinuity sets may not be the same on each side of the camera/scanner line-of-sight. More research on this topic is recommended.

Another form of sampling bias associated with orientation bias, is the underestimation of the intensity/spacing of discontinuity sets oblique to sampling lines or windows. Priest (1993) proposed equations to calculate true intensity/spacing based on apparent measurements. As demonstrated in Chapter 5, such a correction can be applied on remote sensing data the same way it is used on conventional field-based data.
The use of remote sensing techniques introduces another type of bias, related to the observation scale. This concept, also called scale bias, has not received significant attention in the geotechnical literature, although it has been described by some authors. Odling et al. (1999) defined three observation/mapping scales; outcrop scale, which focuses on joint characterization; low-level aerial photograph scale, recognizing joints and faults; and satellite imaging scale, which allows observation of faults. These authors observed that discontinuity orientation is variable over different observation scales. Marret et al. (1999) remarked that discontinuity size populations commonly span over about 10 orders of magnitude.
Observation scale effects should not be confused with the scale effect, as described by Wyllie and Mah (2004), which assumes that, as we consider a rock body at various scales, its discontinuity network remains unchanged. Consequently, discontinuity parameters are considered constant, but depending on the size of an area of interest, slope stability may be controlled by the strength of a single persistent discontinuity or by the strength of a fractured rock mass.

Chapter 4 proposes a description of potential observation scale effects on the quantification of discontinuity orientation and persistence. These include orientation bias, truncation and overestimation of discontinuity persistence. The variation in measurements in relation to observation scale leads to the question as to which scale should be used for rock slope stability analysis. At the rock cut scale, blocks will likely be created by medium- to high-persistence discontinuities (ISRM, 1978). However, at the scale of a large landslide, it may be more appropriate to consider very high- to extremely high-persistence (>40 m) discontinuities. Such discontinuities are generally composed of a combination of finite discontinuities and intact rock fractures.

As a result of the various observation scales, Ortega et al. (2006) state that fracture density and intensity is only meaningful if the fracture detection threshold is quantified and propose the use of cumulative-frequency fracture-size distributions, which have the advantage of facilitating a comparison between scanline data collected at various scales by providing a scale-independent estimation of fracture abundance. Results have to be normalized to a common range of fractures, so that datasets collected at various observation scales can be compared. Ortega et al. (2006), Ortega and Marrett (2000) and Marrett et al. (1999) report that log-log plots of cumulative frequency versus trace length show power-law distributions, suggesting that trace length data at the studied observation scales could be used to predict trace length at other observation scales. More research should be undertaken to correlate fracture intensity measurements from remote sensing sampling windows at various observation scales.
7.2.3 Manual mapping on remote sensing 3D models

In this project, all discontinuities have been mapped manually, as opposed to using available automatic recognition algorithms. A manual approach has the following advantages.

- It allows discrimination between actual discontinuities and rock bridges or other sub-linear/planar features, based on the experience and judgment of the geologist or geotechnical engineer.
- It allows minimization of orientation bias, as in many cases discontinuity traces cannot be automatically delineated.
- It allows minimization of censoring bias, because automatic recognition algorithms tend to subdivide non-perfectly planar discontinuity surfaces into an artificial number of smaller surfaces (Sturzenegger et al., 2007).
- The time involved in observing and mapping remote sensing 3D models provides a preliminary idea on the various discontinuity sets; possible composite surfaces or step-paths; major/critical persistent discontinuities; and potential failure mechanisms.

The disadvantage of using the manual approach is that the application of terrestrial remote sensing techniques does not reduce significantly the time required to map discontinuities. Indeed, instead of measuring fractures in the field along a scanline, geologists/geotechnical engineers must spend that time mapping virtually on a computer. However, time can be saved after manual 3D model mapping, because discontinuity parameters such as location, orientation and persistence are directly stored in a database, which can be readily incorporated into kinematic, limit equilibrium and other slope stability analysis. Slope profiles and DEMs can also quickly be created and incorporated into further analysis.

Discontinuity mean trace length and intensity estimation, using remote sensing topographic circular windows, could be automated using appropriate computer algorithms. Time could then be saved in comparison to traditional field discontinuity mapping, because remote sensing windows could be mapped (semi-) automatically.

Another disadvantage of using a manual 3D model mapping approach is that the amount of discontinuity data provided by 3D models may be less than data measured in
the field. Early published work on the use of terrestrial remote sensing techniques for discontinuity characterization often emphasized that these techniques would allow measurement of an adequate population of discontinuities to define representative statistical definition of parameters such as discontinuity sets and persistence. It is suggested here that such statement was mainly justified by the amount of data provided by automated discontinuity recognition algorithms on close-range outcrops. In many cases, the automated approach, if not used carefully, tends to provide biased parameters, such as censored discontinuity surfaces.

7.2.4 Proposed methods for the quantification of specific discontinuity parameters

A new class of persistence, additional to that defined in ISRM (1978), could be created in response to terrestrial remote sensing measurements. The term “extremely persistent discontinuities” has been used in Chapter 4, for lengths greater than 40 m. Although this persistence class often characterizes composite surfaces, which include various discontinuity sets and some intact rock fractures, these may effectively act as “single” discontinuity at the scale of large rock slopes.

Roughness quantification of point clouds has been undertaken by Haneberg (2007) and Oppikofer (2009) using virtual linear profiling methods and by Grasseli et al. (2002) and Tatone and Grasselli (2009) for the quantification of 3D roughness. All authors agree that roughness quantification is highly dependent on imaging resolution and that outcrop scale (close-range) mapping limits measurements to primary roughness or curvature. Discontinuity roughness measurements based on profiles from TLS/TDP 3D models should be used with care, because of the noise associated with 3D model precision, which may result in artificial roughness. Poropat (2008, 2009) highlights the influence of measurement noise and the importance of point cloud filtering to avoid over-estimation of roughness. The two methods presented in Chapter 3 have the advantage of being less sensitive to noise, because they use a large number of point cloud points. They represent adaptations of available techniques (ISRM, 1978) for the quantification of discontinuity roughness/curvature using 3D photogrammetric or laser point clouds.
Various methods for the quantification of fracture frequency on TLS/TDP 3D models have been tested in Chapter 5. It is argued that using remote sensing window mapping allows consideration of a more representative discontinuity sample than remote sensing scanlines. In addition, it is demonstrated that circular topographic windows in combination with the Mauldon and co-workers’ method (Mauldon et al., 2001) provides the most accurate estimation of areal trace intensity. Intensity results can be further incorporated for the quantification of block size and shape distributions using DFN models.

7.2.5 Incorporation into discrete fracture network models

An approach to incorporate terrestrial remote sensing measurements into DFN model generation has been proposed in Chapter 5. The method of integration supports the use of remote sensing sampling windows, i.e., \( P_{21} \) trace intensity values from remote sensing 3D model windows instead of \( P_{10} \) values from scanline or borehole measurements. It is suggested that the negative exponential distribution of trace lengths is adequate, because it implicitly accounts for discontinuity truncation. This recommendation is based on successive measurements of trace lengths using remote sensing 3D models with varying ground resolutions.

DFN generation requires the input of a number of parameters (mean trace length, trace intensity, discontinuity shape), which can only be estimated, because of sampling bias. In Chapter 5, the cumulative uncertainty resulting from the accumulation of estimated parameters is shown to create highly variable DFN models and block size properties. Consequently, DFN model generation should be undertaken carefully and further research is required to optimize the quantification of trace length, intensity and shape.

7.3 Concluding remarks

This thesis should be used as a guide for the successful application of terrestrial remote sensing techniques in discontinuity characterization and landslide investigations. It includes guidelines concerning the registration of remote sensing 3D models, sampling bias descriptions, discontinuity parameters characterization, volume estimation, cross
section generation, incorporation of 3D model data into both DFN and numerical slope stability analysis. It does not consider displacement analysis using sequential 3D models, which is another important application of terrestrial remote sensing technique in landslide studies (Section 1.3.6).

7.4 Future work

Future work concerning remote sensing characterization of discontinuity parameters and rock slope geometry should focus on the following aspects.

- Development of a method to define the blind zone associated with terrestrial remote sensing projects, based on the analysis of critical parameters, including camera/scanner line-of-sight, ground resolution and rock slope lateral extent.
- Remote sensing 3D model-based quantification of roughness, considering the filtering of point cloud noise: the “areal morphology” method presented in Chapter 3 should be calibrated and possibly correlated with JRC values. An approach to quantify the areal roughness proposed by Renard et al. (2004) uses statistical parameters such as the root mean square (RMS) of a discontinuity surface.
- Optimization of the quantification of trace length, intensity and shape. This would also include further analyses of datasets at various ground resolutions to study the distribution of trace lengths. Parametric studies to examine the relative influence of the various parameters required in the generation of DFN models should also be undertaken.
- Correlation of fracture intensity measurements from remote sensing circular sampling windows achieved at various observation scales.
- Application of terrestrial remote sensing techniques at “near-range”, i.e., at a distance shorter than 5 metres, which may improve the understanding of observation scale effects and provide detailed characterization of discontinuity parameters.
- Study the influence of the incorporation of the topography in 3D numerical models. Initial work on the Mount Seymour road cut highlights the influence of using a detailed topography on the stress distribution and failure kinematics.
Further field work combined with terrestrial remote sensing survey is recommended on both Turtle Mountain and at the Palliser Rockslide.

- Close-range remote sensing should be undertaken on Turtle Mountain to provide detailed characterization of features such as tension cracks.
- The Palliser Rockslide represents a unique case study, because of its well-exposed failure surface. Further detailed characterization of this surface together with an accurate estimation of the volume and chronology of debris is very important in order to constrain future numerical modeling. Additional field mapping at the Palliser Rockslide, and data post-processing work is recommended.
  - Measurements using airborne LiDAR and underwater DEMs should provide a more accurate quantification of the rockslide debris volumes and consequently a better constraint for the pre-slide topography reconstruction.
  - Dating of the two distinct major rockslide debris would provide a temporal constraint.
  - Collection of rock samples for laboratory testing should provide a better constraint of the intact rock and rock mass strength properties, which would provide more confidence in the quantification of intact rock bridge strength and critical percentage.
  - More realistic 3DEC numerical modeling, including a curved failure surface, a more realistic representation of steps/intact rock bridges and deformable block should be tested.
  - A detailed characterization of the discontinuities, fold-related structures and morphology of the “buttress” would allow performing forward analyses of the mountain stability, northwest of the rockslide scar (previous analysis has been achieved by Cruden and Eaton, 1987).

Terrestrial remote sensing techniques should become more routinely integrated in rock slope design and site investigations, and associated with other techniques for discontinuity characterization, including ground penetrating radar (GPR) and acoustic televiwers, allowing for truly tridimensional surveys. In combination, software able to efficiently process remote sensing data should be improved. These should include the development of an automated procedure to apply remote sensing circular window
sampling for the quantification of trace intensity and mean trace length. Similarly, methods for the measurement of discontinuity roughness should be integrated. Such software would allow the optimization of terrestrial remote sensing data and provide, in combination with conventional field-based as well as geophysical measurements, a comprehensive multi-scale quantification of discontinuity and rock slope parameters.

7.5 Reference list


APPENDIX 1: PROPOSED GUIDELINES FOR DISCONTINUITY CHARACTERIZATION AND LANDSLIDE MORPHOLOGIC DESCRIPTION USING TERRESTRIAL REMOTE SENSING TECHNIQUES

This appendix details the procedures developed and used in the field to achieve high quality surveys using both terrestrial laser scanning (TLS) and terrestrial digital photogrammetry (TDP). It describes in detail the post-processing stage used to optimize terrestrial remote sensing data for discontinuity characterization, generation of rock slope profiles, estimation of rock mass volume and combination of both TLS and TDP 3D models. These procedures have been developed using the software packages Polyworks (InnovMetric Software Inc., 2006) and 3DM CalibCam/3DM Analyst (Adam Technology, 2007). The TDP calibration procedure is also detailed.

Terrestrial remote sensing survey for discontinuity characterization: field procedure

Terrestrial laser scanning

- Define the area to be mapped and the topographical constraints, choose the scanner location(s) in order to minimize the potential for occlusion. Some basic structural observations such as the main fractures and discontinuity sets are also recommended to minimize the potential for orientation bias. Major changes in perspective should be accounted for. If several scans are done, enough overlap (10 – 15%) is necessary to merge successfully. Rock mass color and presence of water can limit the scanner range.

- Define the resolution required, which will control the discontinuity truncation level. To do so, an estimation of discontinuity intensity (or GSI) can be helpful. The ground point spacing (EIFOV) of point clouds created with the Optech ILRIS-3D laser scanner depends on the survey distance (Table A1-1). A linear feature or a surface on a rock face requires a certain number of points in order to be mapped. Figure A1-1
can help provide an approximation of the minimum and mean trace length (circle diameter), which can be mapped depending on ground point spacing.

- Define the accuracy required for the project and choose the registration approach accordingly. Various registration approaches are presented and evaluated in Sturzenegger and Stead (2009a and 2009b).
- Scan the rock slope and complete Table A1-2. It could be helpful to draw a sketch of the scene with the locations of scanner and control point positions. Take a digital photograph of the scene.

![Observation scale](image)

**Figure A1-1.** Plots showing the relationship between the minimum (a) and mean (b) equivalent trace length versus ground point spacing and scale (after Sturzenegger and Stead, 2009b).
Table A1-1. Estimation of the ground point spacing (EIFOV) depending on the survey distance (based on Lichti and Jamtsho, 2006).

<table>
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<tr>
<th>Range [m]</th>
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Table A1-2. Laser scanning survey table.

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<tr>
<th>File name</th>
<th>Line-of-sight azimuth</th>
<th>Line-of-sight elevation</th>
<th>Declination</th>
<th>GPS/TS position</th>
<th>Scanner height (at screw)</th>
<th>Associated photographs</th>
<th>Comments</th>
</tr>
</thead>
</table>

Terrestrial digital photogrammetry

- Define the area to be mapped and the topographical constraints, choose the camera locations in order to minimize the potential for occlusion. Some basic structural observations such as the main fractures and discontinuity sets are recommended to minimize the potential for orientation bias. If there are major occlusion zones, orientation bias and/or changes in perspective, several sets of photographs should be taken. The rock face needs to have sufficient texture and/or color variation (a flat, uni-color surface would result in failure of the photogrammetric matching process). Avoid having too much forest/vegetation on a photograph, as this will result in problems during the matching process.

Several model layouts are applicable in order to cover an area to be mapped.

- Independent convergent model (Fig. A1-2a) allows 100% coverage of each photograph and can be used with any focal length over any distance.
Image strips model (Fig. A1-2b) is a series of parallel images overlapping each other by at least 50% (60% to be safe). Horizontal strips can be arranged in multiple rows, overlapping by approximately 15%. Only 1 control points per about 5 images is required to register the model. This model results in poor depth accuracy when using wide-angle lenses (above 28 mm), because of the large distance/baseline ratio, so it is only recommended for wide rock cuts surveyed with low focal length at close-range.

Image fan model (Fig. A1-2c) comprises a series of images overlapping each other by about 10% captured from two or more camera station. The camera must be mounted on a tripod, so that its perspective center stays at the exact same location when taking successive photographs. If this is not the case, photographs should not be assigned to specific camera stations, but considered as a “pseudo image strip model”, when processing them in 3DM CalibCam. This model is recommended when surveying at long-range with high focal length (>50 mm).

For medium and long-range TDP using $f = 200-400$ mm lenses, a project may require taking a large number of photographs. It is recommended to take the photographs systematically (e.g., from right to left and top to bottom, similarly from all camera stations). This will be more practical for the 3D model generation process and recognition of pairs of photographs. It may also be helpful to split a project into several sets of photographs, in order to keep a reasonable number of photographs per project.

Photographs must be taken with the focus at the infinity, which implies a specific minimum survey range in order to obtain non-blurry photographs. The infinity for a $f = 20$ mm lens is at a range of about 3 m, and at about 1500 metres using a $f = 400$ mm lens. If the focus is not at the infinity, a calibration must be done for each individual project.
Figure A1-2. Model layouts. (a) Independent convergent model, (b) image strips model, (c) image fan model (ADAM Technology, 2007; by permission).

- Make sure that the exposure stays constant, especially when photographs contain some sky, otherwise the rock face may appear much darker on these photographs.
- Define the resolution required, which will control the discontinuity truncation level. To do so, an estimation of discontinuity intensity (or GSI) can be helpful. The ground point spacing of photogrammetric 3D model is the ground pixel size multiplied by the step size (typically 4 or 8 pixels) (Table A1-3). A linear feature or a surface requires a certain number of ground points in order to be mapped. Figure A1-1 can help provide an approximation of the minimum and mean trace length (surface diameter), which can be mapped depending on ground point spacing. A spreadsheet provided by Adam Technology (2007) helps estimating the pixel size and the number of photographs needed to cover a defined area (Fig. A1-3).
Table A1-3. Ground pixel size estimation for various lenses and survey distances.

<table>
<thead>
<tr>
<th>Distance [m]</th>
<th>Canon 30D-50 mm lens</th>
<th>Canon 30D-100 mm lens</th>
<th>Canon 30D-200 mm lens</th>
<th>Canon 30D-300 mm lens</th>
<th>Canon 30D-400 mm lens</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.06</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>20</td>
<td>0.3</td>
<td>0.15</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>50</td>
<td>0.74</td>
<td>0.37</td>
<td>0.18</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>1.48</td>
<td>0.74</td>
<td>0.37</td>
<td>0.19</td>
<td>0.1</td>
</tr>
<tr>
<td>200</td>
<td>2.96</td>
<td>1.48</td>
<td>0.74</td>
<td>0.37</td>
<td>0.18</td>
</tr>
<tr>
<td>500</td>
<td>7.39</td>
<td>3.69</td>
<td>1.85</td>
<td>0.93</td>
<td>0.47</td>
</tr>
<tr>
<td>1000</td>
<td>14.78</td>
<td>7.39</td>
<td>3.7</td>
<td>1.85</td>
<td>0.93</td>
</tr>
<tr>
<td>1500</td>
<td>22.17</td>
<td>11.08</td>
<td>5.54</td>
<td>2.77</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Figure A1-3. Spreadsheet provided by Adam Technology for planning photogrammetric surveys.

- Define the accuracy required for the project and choose the appropriate registration approach. Various registration approaches are presented and evaluated in
Sturzenegger and Stead (2009a and 2009b). Choose the appropriate distance/baseline ratio (a ratio situated between 5/1 and 8/1 is recommended).

For medium and long-range TDP, using \( f = 200-400 \) mm lenses and a large number of photographs, it can be helpful to take photographs from three camera stations using a tripod (even if these stations are not surveyed using a GPS or TS). The ability to group photographs from two or three relative positions seems to facilitate the software 3DM CalibCam resection and bundle adjustment processes (probably reducing the number of unknowns).

- Survey the rock slope and complete the Table A1-4. It could be helpful to draw a sketch of the scene with the names of camera and control point positions. Consult the “Image capturing quick start guide” (Adam Technology, 2004) in order to optimize photograph quality.

<table>
<thead>
<tr>
<th>Camera position</th>
<th>Camera height</th>
<th>Baseline distance</th>
<th>Camera line-of-sight azimuth</th>
<th>Camera line-of-sight elevation</th>
<th>Tilt</th>
<th>Lens focal length</th>
<th>Approach E: azimuth between horizontal targets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A1- 4. Digital photogrammetry survey table.
Registration of remote sensing 3D models: post-processing workflow

The various 3D model registration approaches are presented in Chapters 3 and 4 (Sturzenegger and Stead, 2009a and 2009b). This appendix provides the post-processing workflow, after the field survey has been completed. The commands used are shown in square brackets.

Approach A

Approach A uses only a compass to measure the laser scanner/camera line-of-sight. It allows registration of a 3D model in a relative oriented reference system. Using a compass, the declination must be accounted for.

Polyworks IMInspect and laser scanner point clouds

- Create a reference point at the position of the scanner, i.e., coordinate (0,0,0) [on the tree bar, right click on reference point – create]. A reference point may have been created previously in IMAlign.
- Create a primitive point at the location of this reference point.
- Rotate the point cloud around the reference point [align - manual alignment - 3D rotation; select the reference point - click “from point”; check “x” and enter the compass elevation measurement (positive if the line-of-sight is upwards); check “z” and enter the compass azimuth measurement (negative clockwise, to the East); select the point cloud in the treebar and click “apply”].
- If the true (GPS) position of the scanner is known, it is possible to translate the now oriented point cloud, i.e., register it in a global geographic reference system [align - set huge translation – file - open point cloud - select GPS survey - check template and choose “name + points”].

3DM CalibCam and photogrammetry

- Create a new project, import images and generate relative-only points
- Enter the distance between two camera stations [scale bar]
- Run the resection to obtain the relative camera positions [exterior – free network – resection]
In the image setting of the resection window, enter manually the compass measurements: omega = -(90 + compass elevation), phi = 0, kappa = -(360 – compass azimuth)

Run the bundle adjustment only. There is no need for resection, because the compass measurements already provide an approximation of the camera exterior orientation parameters.

If the registration does not work this way, try to use kappa = azimuth-180°. This will rotate the 3D model by 180°. Therefore, all measured discontinuity dip direction will then have to be rotated by 180° to obtain the correct values.

**Approach B**

Approach B uses three surveyed camera/scanner positions to register a 3D model in a global geographic or relative reference system.

*Polyworks IMAlign, IMInspect and laser scanner point clouds*

- In IMAlign, merge the three point clouds and create reference points for the three scanner positions.
- In IMInspect, translate the point cloud so that the point coordinates are close to the coordinate of the surveyed scanner positions [align - huge translation; file - open point cloud - select the survey file (ascii) making sure the order of information in the file is the same as the one on the template box (usually “name + points”); if the required template does not appear, press advanced and select from the list; make sure the box at the bottom is checked if the ascii file order is north, east, elevation].
- Import the surveyed scanner positions [file - import primitive - points from text file (make sure to have the “name + points” template as previously)].
- Create a primitive point for each created reference point (scanner position).
- Align the scanner location with the surveyed positions [align - N pairs of center points].

*3DM CalibCam and photogrammetry*

- Add three camera stations and follow the procedure presented by Adam Technology (2007). Make sure to account for camera heights for the surveyed camera stations.
Approach C

Approach C uses three or more surveyed target positions to register a 3D model in a global geographic or relative reference system.

*Polyworks IMInspect and laser scanner point clouds*

- Translate the point cloud so that the point coordinates are close to the coordinate of the surveyed scanner positions [align - set huge translation; file - open point cloud - select the survey file (ascii) making sure the order of information in the file is the same as the one on the template box (usually “name + points”); if the required template does not appear, press advanced and select from the list; make sure the box at the bottom is checked if the ascii file order is northing, easting, elevation].
- Import the surveyed scanner positions [file - import primitive - points from text file (make sure to have the “name + points” template as previously)].
- Digitize the point cloud the targets used as control points. The dataset being a point cloud with a specific point spacing, a point corresponding to the target centre may not exist. Consequently, for more accuracy, it is recommended to select a group of points corresponding to an entire target, fit a primitive (a circle, for example) and create a point at its center. Using this method, the digitized point corresponds to the true center of the target.
- Align the scanner location with the surveyed positions [align - N pairs of center points].
- Check the accuracy of the alignment procedure [on the tree bar select item - center points].

*3DM CalibCam and photogrammetry*

- Follow the procedure presented by Adam Technology (2007).

Approach D

Approach D uses a combination of surveyed camera/scanner and target positions to register a 3D model in a global geographic or relative reference system. The procedure is similar to the one presented for approaches B and C.
Approach E

Approach E uses three targets located at right angle, indicating the vertical and horizontal axis of an oriented relative reference system. A compass is used to measure the azimuth of the horizontal axis and a tape measure to measure the vertical distance. This approach is used mostly for photogrammetric surveys, in 3DM Calibcam. Using a compass, the declination must be accounted for.

- Digitize the targets, define the scale.
- Run the resection [exterior – free network – z axis from point a to point b (positive upwards), horizontal axis from point c to a (positive northwards or westwards)].
- Run the bundle adjustment.

Pre-registered 3D model approach

This approach transmits a pre-registered 3D model coordinate system to a non-registered TLS/TDP 3D model. This can be done using 5-10 features recognizable on both point clouds, which is equivalent to approach C. However, in certain cases (e.g., when the resolution of the two 3D models is different), difficulty in recognizing specific features may cause this approach to be relatively inaccurate.

An alternative, more accurate, approach is to fit the non-registered 3D model on the pre-registered one using the best alignment procedure in Polyworks.

- In IMAlign, import both the pre-registered and non-registered point clouds, align them and export the alignment matrix.
- In IMInspect, import the non-registered point cloud (and associated files, such as the file containing the mapped discontinuities) and apply the alignment matrix to all files together.

Discontinuity mapping on TLS/TDP 3D models

Discontinuity position, orientation and persistence; discontinuity sets

Discontinuities are mapped manually, using raw point clouds or meshed/triangulated surfaces, by fitting circular planes on recognizable surface or traces
with enough relief. Mapping should be achieved with care in order to minimize sampling bias including orientation and various length bias (Chapter 3: Sturzenegger and Stead, 2009a), and observation scale effects (Chapter 4: Sturzenegger and Stead, 2009b).

*Polyworks IMInspect and laser scanner point clouds*

- Fit a plane on a selection of 3D model points. Digitize a primitive point at the centre of the plane. Fit a circle centered on this point, having the orientation of the plane.
- The properties of the created circle are exported [select all circles - right click – export to text file] and include:
  - The position of the center of the circle
  - Circle’s normal direction cosines, from which discontinuity dip and dip direction can be derived (see later in this Appendix).
  - Discontinuity persistence, expressed either as the area of the circle or as an “equivalent trace length” representing the diameter of the circle.
  - Discontinuity sets can be defined by importing circle parameters into Rocscience Dips or similar software.

*3DM Analyst and photogrammetry*

- Discontinuities are mapped using the procedure presented by Adam Technology (2007).
- If necessary, mapped discontinuities can be exported [feature info – feature info list – save to file] and imported in IMInspect [right click on circle – import - circle with points+vectors+radii+names]. Discontinuity dip and dip direction need to be converted into the circle’s normal direction cosines (see later in this Appendix).

*Mapping apparent surfaces*

Discontinuities can also be mapped as apparent surfaces of a 3D model, using either IMInspect or 3DM Analyst.

- Map discontinuity surfaces using polylines (if 3DM Analyst was used, then export the polylines using the .maf format and prepare the file so that it can be recognized by IMInspect).
- Select all polylines and close them [right click – edit – close]
Define a sampling window using another polyline and create a plane with the mean orientation of the sampling window.

- Project all polylines onto the created plane [right click – edit – project onto plane].
- This procedure allows comparing the total area of apparent discontinuities with the area of the sampling window in order to quantify the percentage of the rock slopes occupied by fracture/rock bridges (see example in Section 6.4.3).

**Roughness and curvature**

**Areal morphology**

In IMInspect, select the point cloud points of a specific discontinuity and compare them with the mapped discontinuity plane [compare – data to primitive – select the discontinuity plane (it has to be a plane, not a circle) – choose the “shortest distance” option]. The roughness/curvature is expressed as an error map of the distance between the discontinuity plane and the point cloud.

**Virtual compass and disc-clinometer**

Orientation measurements are achieved at numerous places on a discontinuity by selecting point cloud points in areas of progressively increasing size. The average orientation of each of these areas is then plotted on stereonets and the roughness angle measured.

**Intensity, block size/shape**

Trace intensity, block size and shape can be quantified using remote sensing topographic circular sampling windows. The methodology is presented in Chapter 5 (Sturzenegger et al., in prep.).

- If using photogrammetric data, export photogrammetric DTMs using .maf format from 3DM Analyst and convert it into an ascii text file (clean extra columns using Microsoft Excel or Access). Import the ascii file in IMInspect. (It is also possible to import .maf files converted to text files and account for the extra columns by specifying “name + points”.)

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- Select the approximate area of the point cloud where the circular window needs to be created. Fit a circle with a selected radius (or fit a plane, define a center point, create a circle with the plane orientation and the point as center). This will create a circular window having the mean orientation of the selected part of the rock slope.
- Orient the circular window with a view approximatively parallel to the normal of the circle and manually select all the point cloud points projecting inside the window, by following the perimeter of the circle. Invert the selection and delete, so that only the points within the circular window remain. The remaining point cloud points create a topographic circular window.
- Import the mapped discontinuities. Count the number of discontinuities intersecting the circular window perimeter (i.e., partly contained) to obtain the number “n”. Count the number of discontinuities, which are completely contained in the circular window to obtain the number “m”.
- If using a planar circular window, create a trace map by fitting a vector along the intersection of discontinuities with the sampling window. Using a planar circular window is likely to under-estimate trace intensity (Chapter 5: Sturzenegger et al., in prep.).
- The obtained value for trace intensity represents $P_{21}$, which can be incorporated into discrete fracture network (DFN) models. The procedure to derive block size and shape in detailed in Chapter 5 (Sturzenegger et al., in prep.).

**Other tools for landslide investigation**

**Cross sections**

- To create a cross section, go to [edit – cross section] and choose one of the available options. To incorporate deterministically a discontinuity along this cross section, measure the intersection with a plane parallel to the cross section.
- Display a plane view of the created cross section [view - pose - +z].
- Rotate the cross section manually so that it is parallel to the x- or y-axis [align - manual alignment – rotate around z-axis].
- Export the cross section as a text file, one of the columns (x or y) should have almost constant coordinates and must be deleted (using Microsoft Excel or Access) to create a 2D profile.
- The cross section may have some noise, which should be filtered, in order to simplify the profile and also to get rid of artificial roughness/relief. To do that, export the cross section and open it in Microsoft Excel. If there are too many points, delete every second or third point. Then view the cross section as a XY chart (enlarge many times if necessary) and go through the section to find the main topographical features (breaklines, etc.). Based on this careful observation, it is possible to simplify the cross section by reducing the amount of points, keeping more points where there are relevant topographical features. If incorporating them into numerical models, the cross sections should be simplified as much as possible, while still keeping the main features of the topography.

**Volume estimation and reconstruction of pre-slide topography**

To calculate a volume, create a plane representing a specific discontinuity or an average orientation; keep only the 3D models points located on one side of this plane (delete the others); triangulate the point cloud to generate a mesh; calculate the volume situated between the mesh and the plane. More detailed can be found in the Polyworks manual.

In order to measure the volume of a landslide debris (or similar landform), the following method was used.

- Use a 3D model or DEM and measure the volume between an arbitrary plane located below the landslide debris and an area including the entire debris (using the above technique)
- Re-shape the same DEM, i.e., delete the points corresponding to the debris and interpolate the pre-slide topography based on morphological observations. The interpolation can be done using a variety of tools, e.g., a plane linking remaining points in the DEM and/or additional points representing breaklines of the landscape.
These additional points can then be exported and incorporated into the ascii file of the pre-slide DEM.

- Use the pre-slide DEM just created and measure the volume between the same arbitrary plane used previously and the same area including the entire debris.
- The volume of the debris is the difference between the pre-slide and post-slide volume measurements. The thickness of the debris can be obtained by comparing pre- and post-slide data, using the “compare” options.

The same method can be used to create a reconstruction of a pre-slide rock slope.

**Combining TLS and TDP data to create a composite 3D model**

The following section describes the procedure used to merge and register TLS and TDP 3D models. It is slightly more complicated than the IMAlign merging procedure, because there is very little or sometimes even no overlap between adjacent 3D models.

- Display the first point cloud in IMAlign and create a reference point at the digitizer position. Make sure its position is (0,0,0).
- Manually register the point cloud using approach A.
- Apply a translation, equal to the xyz coordinates of the first laser scanner position, to the position of surveyed targets (i.e., subtract the xyz values of the first laser scanner position from all surveyed points). The positions of all surveyed targets are now artificially translated so that the coordinates of the first scanner position is (0,0,0).
- Digitize a reference point (anchor) of a known target position on the point cloud.
- Create another reference point with the surveyed coordinates of this point.
- By trial and error, align the two reference points [successively align manually the point cloud and re-digitize the target point, until the target point on the point cloud is at the same position as the surveyed target point].
- Create reference points for all surveyed targets and camera/scanner locations.

The point cloud is now oriented relatively to the north and all surveyed targets and camera/scanner points are located in the same relative reference system.

- Lock the first scan.
- Import the next scan and create a reference point at its digitizer position.
- Merge using digitized targets and any available additional recognizable feature (the digitizer position reference point cannot be used for merging, but it will be useful to check the accuracy of the alignment).
- Run the best-fit alignment and merge other scans applying the same procedure.
- To include TDP 3D models (ascii unorganized point clouds), they must be in the same reference system. Therefore, the whole project with laser scanning point clouds has to be translated back, using the “huge translation” option and the surveyed target file.
- To help with the merging of various 3D models, remember that:
  o Locked point clouds means that they will not move during the merging process,
  o Selected, unlocked point clouds means that they will move during the merging process.
- Once all point clouds have been merged, run the “overlap reduction” option and save the IMAlign project. It is also possible to export the rotation matrices of each individual 3D model.
- Import the IMAlign project in IMInspect (or open individual 3D models and align them using the rotation matrices). Register the final composite 3D model, using approach C.
- To open the composite model in ArcGIS, export from IMInspect as an ascii file. Then, since there is an overhang, we need to have an “equivalent plane view”, i.e., x and y coordinates need to be switched (use Microsoft Excel or Access to do that).

  The accuracy of the composite 3D model must be evaluated.

- Factors contributing to the overall error include the laser scanner, as advertised by Optech Inc. (2008); the DGPS survey; the Polyworks alignment procedure (evaluated using digitizer positions and associated surveyed points); and the target recognition.
- The accuracy can also be evaluated by comparing the composite 3D model with the existing airborne LiDAR DEM. To do that, both models are aligned in IMAlign and their rotation matrices exported. Then, in IMInspect, both models are imported and aligned using the matrices. Using the “compare” option, an error map can be created.
Note that the number of points being very large, the model needs to be subdivided in order to be triangulated. Then, all the triangulated models can be displayed at once, and cross sections and other options can be used.

The comparison may highlight irrelevant features, like trees, which need to be filtered. Using IMInspect in version 9, vegetation removal has to be done manually, or by creating planes underneath the vegetation and deleting the points located above them (Only Polyworks version 10 has a vegetation removal tool. Using version 9, it is possible to remove trees using IMMerge to create a solid model of the data and then load the model as a reference object in IMInspect. After loading the data in IMInspect use select-data-by-reference object. This allows highlighting the data to be filtered.)

Camera/lens Calibration using 3DM CalibCam

Calibration using the software 3DM CalibCam (Adam Technology, 2007) requires photographs taken from six camera positions (or at least three) arranged in a pyramidal setting (Fig. A1-4). At each position, photographs should be taken both horizontally and vertically. Depending on the lens, the distance to the rock face must be large enough, so that focus at infinity can be reached.

![Figure A1-4. Calibration field setting. The circles represent camera positions.](image)

- Turn off the “auto rotate” option of the camera: The images must be as seen by the image sensor to allow the software to determine the connection between the two.
- In 3DM CalibCam, create a new camera file [add new camera] and enter known parameters, including name, image size, pixel size, lens type, camera type, advertised focal length. Some information about cameras can be found at www.dpreview.com.
- Bring the new camera file into a new project, add the photographs and rotate the vertical ones.
- Digitize relative-only points, run the interior resection and bundle adjustment and delete bad points. If the adjustment does not work, try to vary the initial focal length input value.
- Look at the bundle adjustment report. The correlation matrix indicates the relative influence of each interior orientation parameter. Try to reduce the number of redundant parameters by zeroing some of them and checking their fix box (from right to left) [setting – camera calibration]. The report also indicates which parameters have the most influence on the final error, allowing zeroing the ones, which have less influence. The sigma value should stay as close to 1 as possible.
- Once the calibration is ready, save it [right click on the camera – edit camera data – save].

Large lenses \( (f = 200-400 \text{ mm}) \) can be difficult to calibrate, because the depth of field (relative to the range) is narrow, making it harder to get a lot of depth into the scene. In order to capture a larger area (and more depth), it is possible to use image fanning from each camera position. This means, for example, taking a grid of 3x3 photographs with a 50% overlap between adjacent images. Calibration of large lenses also requires long distances between camera positions and object (it is not possible to use the side of a building from 20 metres, as can be done with a small lens). Finally, photographs should be taken carefully so that they are not blurry. 3DM CalibCam provides an image of calibrated camera/lens distortion. A calibration with an irregular distortion pattern is harmless. It means that the image sensor is not perfectly aligned with the perspective centre of the lens.

**Conversion of direction cosines to dip/dip direction angles**

The orientation of a normal vector to a plane (discontinuity) in IMInspect is expressed by its direction cosines:

\[
\begin{align*}
x &= \cos X \\
y &= \cos Y \\
z &= \cos Z
\end{align*}
\]  
\( \text{(A1-1)} \)
where $X$, $Y$ and $Z$ are the angles of the normal vector with respect to the x-, y- and z-axis. The x-axis points eastwards, the y-axis northwards and the z-axis upwards.

According to Goodman (1989), if a normal to a plane rises at angle $\delta$ above horizontal in a direction $\beta$ measured counterclockwise from north, the direction cosines of the normal to the plane are:

$$l = \cos \delta \cos \beta$$
$$m = \cos \delta \sin \beta$$
$$n = \sin \delta$$  \hspace{1cm} (A1-2)

In Goodman’s reference system, the x-axis points northwards, the y-axis westwards and the z-axis upwards. Consequently, Eq. A1-2 must be adapted as follow:

$$\cos(180 - X) = \cos \delta \sin \beta$$
$$\cos Y = \cos \delta \cos \beta$$
$$\cos Z = \sin \delta$$  \hspace{1cm} (A1-3)

Then, using Eq. A1-3:

$$\beta = \arctan \left( \frac{\cos(180 - X)}{\cos Y} \right)$$  \hspace{1cm} (A1-4)

$$\delta = \arcsin(\cos Z)$$  \hspace{1cm} (A1-5)

Finally:

If $\delta \geq 0$, then $\text{dip} = 90 - \delta$ \hspace{1cm} (A1-6)

If $\delta < 0$, then $\text{dip} = 90 + \delta$ \hspace{1cm} (A1-7)

And

If $0 \leq \beta \leq 90$ and $\delta \geq 0$, then $\text{dip direction} = 180 - \beta$ \hspace{1cm} (A1-8)

If $0 \leq \beta \leq 90$ and $\delta < 0$, then $\text{dip direction} = 360 - \beta$ \hspace{1cm} (A1-9)

If $-90 \leq \beta < 0$ and $\delta \geq 0$, then $\text{dip direction} = -\beta$ \hspace{1cm} (A1-10)

If $-90 \leq \beta < 0$ and $\delta \leq 0$, then $\text{dip direction} = 180 - \beta$ \hspace{1cm} (A1-11)
Using IMInspect, depending on the direction of plane’s normal, the signs of direction cosines may be inverted. This would create errors in the conversion to dip direction. So:

i. add 180 to the dip direction obtained from Eqs. A1-8 to A1-11 if:
   - $X<0$, $Y<0$ and $Z>0$, or
   - $X<0$, $Y>0$ and $Z>0$, or
   - $X=0$, $Y<0$ and $Z>0$, or
   - $X<0$, $Y=0$ and $Z>0$,

ii. subtract 180 from the dip direction obtained from Eqs. A1-8 to A1-11 if:
   - $X<0$, $Y<0$ and $Z<0$, or
   - $X<0$, $Y>0$ and $Z<0$, or
   - $X=0$, $Y>0$ and $Z>0$, or
   - $X=0$, $Y>0$ and $Z<0$, or
   - $X<0$, $Y=0$ and $Z<0$.

The previous equations have been incorporated in a spreadsheet, which can be used to obtain discontinuity dip and dip direction from direction cosines data provided by IMInspect. Inversely, another spreadsheet allows converting dip and dip direction into direction cosines.

**Reference list**

APPENDIX 2: LONG-RANGE TERRESTRIAL DIGITAL PHOTOGRAMMETRY FOR DISCONTINUITY CHARACTERIZATION AT PALABORA OPEN-PIT MINE

The following appendix has been published as:


Abstract

This appendix documents a field survey using long-range terrestrial digital photogrammetry at the Palabora open-pit mine, South Africa, for multi-scale characterization of rock mass discontinuities. Stereomodels covering the entire mine were generated based on photographs taken from a distance of 1600 m across the pit, using a series of \( f = 20-400 \) mm lenses. Details on the methodology used and its accuracy are discussed. Preliminary results on discontinuity orientation, persistence and intensity are presented, highlighting the effect of observation scale. The potential uses of long-range terrestrial digital photogrammetry in open-pit mine and large natural rock slope environments is emphasized. The use of an \( f = 400 \) mm lens from distances larger than 1.5km may represent an important step forward in the geotechnical characterization of inaccessible remote rock faces.

Introduction

Terrestrial digital photogrammetry (TDP) is now routinely applied in rock mass discontinuity characterization of both natural and engineered rock slopes. Discontinuity mapping on photogrammetric stereomodels allows measurement of discontinuity geometric properties, which include discontinuity position, orientation, persistence, roughness, frequency and block size. Several authors, including Krosley et al. (2006), Martin et al. (2007), Coggan et al. (2007), Haneberg et al. (2006), Haneberg (2007) and
Sturzenegger and Stead (2009a), have highlighted the accuracy and potential of photogrammetric techniques. Software allowing both stereomodel generation and discontinuity characterization are available (Gaich et al., 2006; Birch, 2006; Poropat, 2006) and are designed to be used by non-photogrammetrists, i.e., geologists and geotechnical engineers.

Until now, TDP has been applied predominantly on individual benches or roadcuts, at close-range. Characterizing larger rock slopes at medium- to long-range represents a logical development (Sturzenegger and Stead, 2009b). Large rock slopes may be represented by entire mountain cliffs or open-pit slopes at scales ranging from the multibench to entire pit wall. Using TDP on large rock slopes can solve obvious issues related to accessibility and hazard. In addition, it allows accurate assessment of the properties of large structures that may potentially affect slope stability.

The current appendix summarizes the challenges faced and presents preliminary results in the application of long-range TDP for discontinuity characterization at the Palabora open-pit mine, South Africa. Photographs were taken across the diameter of the pit from a distance of 1600 m. Complete sets of photographs, covering the entire pit, were obtained using $f = 20$ mm, 55 mm, 100 mm and 200 mm lenses and partial coverage of the walls were achieved using a $f = 50$ mm and 400 mm lens. Multi-scale discontinuity characterization is being achieved on these stereomodels and the results at selected locations are presented. This data highlights the need to consider the effect of observation scale in the planning phase of a long-range photogrammetric field survey.

**The Palabora Mine**

Located approximately 390 km North East of Johannesburg, the Palabora copper mine began open pit operations in 1964. Surface excavations ceased in 2003, and since then the mine has been operating as an underground block cave operation. Following the inception of the underground activities beneath the north wall of the open pit, cracking was observed in the northern pit wall during 2003. As caving progressed, so the wall disturbance increased, ultimately leading to the development of an approximately 800 m high failure of the north wall.
The Palabora Igneous Complex consists of a succession of subvertical pipe-like bodies of alkaline and ultramafic rocks that have intruded the surrounding Archean granite (Piteau Ass., 2005). The copper orebody occurs in the Loolekop pipe emplaced in pyroxenite host rock and contains successive intrusions of micaceous pyroxenite, foskorite and banded carbonatite. Subvertical, northeasterly trending dolerite dykes cut across the complex. Four large scale faults, striking WSW, WNW and S, cross the open pit. Three dominant discontinuity sets are ubiquitous within the mine.

Terrestrial digital photogrammetry

Photogrammetry was carried out using a Canon 30D and a Canon XTI digital SLR cameras, with $f = 20$-400 mm lenses. All images have been processed using the software 3DM Calibcam and 3DM Analyst (Adam Technology, 2007). In addition, models have been imported into Maptek Vulcan (2008) for further analysis and presentation. Photogrammetric models of the entire pit were made using $f = 20$ mm, 55 mm, 100 mm and 200 mm photographs (Fig. A2-1), while $f = 50$ mm and 400 mm models were generated at specific locations to provide more details of the topography.
Figure A2-1. $f = 20$ mm stereomodel of the entire open pit, providing a general view of the mine. The diameter of the pit is approximately 1600 m.

**Network setting**

All stereomodels were generated within the mine grid, using control stations set out by the mine survey department. A few additional control points and the camera positions were added to the network and surveyed for the photogrammetric survey (Fig. A2-2). A baseline approximately equal to 1/6 of the distance between the camera and the imaged rock face was used and in some cases, three camera stations per photogrammetric model were used. The images were captured using an image fan model layout (Adam Technology, 2007).

The north, east, south and west walls of the pit were covered by four different sets of photographs, in order to locate the camera stations sub-perpendicular to each wall. For the $f = 200$ mm and $400$ mm models, where a large number of photographs were required to cover entire walls, the sets of photographs were split in two or three sub-sets in order to create two or three stereomodels with a manageable amount of images (in terms of digital photomodel size).
Figure A2-2. Network of surveyed points, including control targets (red filled circles) and camera locations (white circles) (after Beveridge et al., 2008).

Accuracy

Because of the limited number of available mine control points (15 over the entire pit), these could only be used in the registration of the low resolution models ($f = 20$-$55$ mm). Some inaccuracy in the model registration can be expected because of the non-optimal sizes/shapes of the control points. Prisms located at the top of permanent survey rods are sub-optimal, because the poles are too thin to be represented on stereomodels. The prisms located on top of massive concrete monuments were usually adequate; the best control points being provided by large targets painted directly on the rock walls.

As mentioned previously, at higher resolution, the sets of photographs had to be split into sub-sets, which individually did not contain enough control points for
registration. Consequently, \( f = 100 \) to 400 mm models were registered by transfer of control from selected recognizable features in the 55 mm model. Since this model had been registered, any point could potentially be used as a control point. It must be noted that absolute errors in the 55 mm model are consequently transmitted to the higher resolution models. Maximum inaccuracy of -3.7, 4.2 and 0.6 m in the x, y and z coordinates, respectively and maximum imprecision of 5.0, 6.5 and 1.5 m in the x, y and z coordinates, respectively have been measured on the \( f = 55 \) mm model. As the predominant use of models is in the measurement of relative dimensions/orientations (not absolute coordinate), the obtained accuracy and precision are considered adequate for rock mass characterization.

Based on a comparison of discontinuities mapped on a specific bench of the north wall both from a 1600 m distance using \( f = 400 \) mm lens (long-range) and at a 30 m distance with the \( f = 50 \) mm lens (close-range), Fig. A2-3 shows that there is a good consistency between stereonets. This suggests that the methodology provides accurate discontinuity orientation measurements for rock engineering purposes.

![Figure A2-3](image)

Figure A2-3. Equal angle, lower hemisphere stereonets with poles of discontinuities mapped using \( f = 50 \) and 400 mm lenses on a selected bench in the north wall. \( f = 50 \) mm mapping was carried out at a 30 m distance and \( f = 400 \) mm at a 1600 m distance (after Beveridge et al., 2008).
Ground resolution

Table A2-1 summarizes ground point spacing for each focal length used. Ground point spacing is the distance between spatial points in the stereomodels and represents the product of the ground pixel size and the step size (number of pixels, both horizontally and vertically, used to generate one spatial point).

Table A2-1. Ground point spacing and observation scale for the various stereomodels (after Beveridge et al., 2008).

<table>
<thead>
<tr>
<th>Focal length [mm]</th>
<th>Distance [m]</th>
<th>Ground point spacing [cm]</th>
<th>Observation scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1600</td>
<td>365</td>
<td>Wall</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>3</td>
<td>Bench</td>
</tr>
<tr>
<td>55</td>
<td>1600</td>
<td>133</td>
<td>Wall</td>
</tr>
<tr>
<td>100</td>
<td>1600</td>
<td>82</td>
<td>Wall</td>
</tr>
<tr>
<td>200</td>
<td>1600</td>
<td>41</td>
<td>Wall</td>
</tr>
<tr>
<td>400</td>
<td>1600</td>
<td>21</td>
<td>Wall/Bench</td>
</tr>
</tbody>
</table>

Specific issues to be addressed in photogrammetric pit wall survey

To ensure the quality of stereomodels, pairs of photographs should be taken within a short period of time to avoid changes in lighting of the walls. This condition was sometimes difficult to adhere to, because of the distance between successive camera positions (several hundreds of metres and on different benches). Consequently, when the weather is characterized by an alternation of sun and clouds, the conditions can be sub-optimal. In addition, field work must be carefully planned so that the walls illuminated by the sun at a certain time of the day are surveyed at the appropriate time.

Another fieldwork component, where difficulties may be encountered, is in the calibration of long focal length \( f = 200 \) and 400 mm lenses. Calibration is an important step in the photogrammetric process, necessary to calculate the exact focal length of a lens and to quantify internal camera parameters. With large focal lengths, the network of successive camera locations used for calibration (see Adam Technology, 2007), involves large distances. Consequently, for the same reasons as highlighted in the previous paragraph, optimal weather conditions may be difficult to attain. In addition, at such large
ranges, it may be difficult to survey a rock slope with relatively sufficient relief, a requirement for good calibration. Calibration may, however, be conducted after the field survey at a location optimal for maximizing success.

**Discontinuity characterization**

To date, a total of 2808 discontinuities have been manually mapped on the various focal length stereomodels. At this stage, characterization on the $f = 55$ and 100 mm models covers both the north and west walls, while on the $f = 50$, 200 and 400 mm models, it is concentrated predominantly in specific areas of the north walls. Characterization using various resolution stereomodels must be applied with care because of the potential for observation scale effects. Sturzenegger and Stead (2009b) summarized the effects of observation scale on discontinuity orientation and persistence. While high resolution stereomodels usually allow the most detailed characterization, lower resolution can be useful in the recognition of highly persistent features, which can be critical for wall stability.

The numerous images required to cover the pit walls at $f = 100$ mm, 200 mm and 400 mm resolutions has presented some issues for simultaneously displaying a large number of stereomodels on computer screens. This was particularly problematic for the characterization of large features, which cross several stereomodels, and where censoring issue must be considered. As this limitation is a function of computing processing/memory facilities and not a limitation of high focal length imagery, it is considered that future censoring problems will be more easily addressed.

**Discontinuity orientation**

Figure A2-3b and Table A2-2 show the orientation of discontinuities mapped on the north wall, using the $f = 400$ mm stereomodels. Four sets have been recognized, three of which are approximately orthogonal to each other. Discontinuity sets 1 to 3 agree well with those described by Piteau Ass. (2005) as present throughout the open pit.
Table A2-2. Discontinuity orientation on the north wall using the $f = 400$ mm stereomodels.

<table>
<thead>
<tr>
<th>Discontinuity set</th>
<th>Dip [°]</th>
<th>Dip direction [°]</th>
<th>Piteau (2005) discontinuity set Dip/DipDir[°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70</td>
<td>235</td>
<td>80/225</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>351</td>
<td>80/320</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>276</td>
<td>80/270</td>
</tr>
<tr>
<td>4</td>
<td>03</td>
<td>063</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**Discontinuity persistence**

Persistence is expressed as the diameter of the mapped discontinuities, which is termed “equivalent trace length” for comparison with field surveys. Figure A2-4 shows the “equivalent trace length” distribution of discontinuities mapped on the north wall using both $f = 100$ and 400 mm stereomodels. It is notable that there is a shift of the distribution to the left, i.e., towards shorter persistence, when the ground resolution increases. This effect of observation scale has been studied by Sturzenegger and Stead (2009b) and suggested regression equations were proposed as a planning tool to evaluate the required focal length for mapping specific discontinuity persistence.
A preliminary attempt to estimate fracture intensity have been undertaken. Areal fracture intensity represents the total length of all fractures intersecting a sampling window, divided by the window area. It is termed “P_{21}” in the FracMan code (Golder Associates Inc., 2008). A 10 m diameter virtual window with average slope orientation has been delineated on stereomodels of a specific bench of the north wall. Trace maps have been created as illustrated in Fig. A2-5 and areal fracture intensity directly calculated. This process has been repeated using the various focal length stereomodels.

It is important to highlight that the delineation of a sampling window with an averaged rock slope orientation can be expected to bias fracture intensity estimation. Indeed, small discontinuities, having a size smaller that the magnitude of the irregular rock face relief, will be omitted. Research on appropriate photogrammetric windows for
estimation of fracture intensity is ongoing*. Notwithstanding, the preliminary results obtained from this study of fracture intensity provide an interesting observation concerning the effect of observation scale. Figure A2-6 shows the variation in areal fracture intensity ($P_{21}$) with respect to ground point spacing.

![Figure A2-5](image)

Figure A2-5. Areal fracture intensity estimation. (a) 10 m diameter circular sampling window, (b) mapped discontinuities, (c) discontinuities intersecting the window, (d) traces of these discontinuities (after Beveridge et al., 2008).

*The result presented in Chapter 5 (Sturzenegger et al., in prep.) show that topographic circular sampling windows provide a better estimation of fracture intensity than planar windows used in this preliminary study. Consequently, it is now recommended to refer to the methodology developed in Chapter 5.
Figure A2- 6. Graph illustrating a decrease in $P_{21}$ value as ground pixel spacing increases.

Discussion

The author successfully applied long-range terrestrial digital photogrammetry in a large open-pit mine, at Palabora. At this mine, it is no longer possible to obtain access to pit walls for conventional mapping due to safety concerns. Previous data were obtained during the life of the open pit. As the orebody contains magnetic rock types, this is also a factor in conventional mapping. Further data on the fracture networks is required to allow the application of state-of-the-art modeling codes with increased confidence (Vyazmensky et al., 2009; Sainsbury et al., 2008). This appendix presents an extension of conventional rock engineering photogrammetry to long-range high focal length applications. During the fieldwork and subsequent stereomodel generation, practical difficulties encountered included:

- Registration of stereomodels with a limited number of control points, due to the lack of optimal and accessible targets,
- Lighting issues, non-optimal weather conditions necessitating careful planning of fieldwork according to the position of the sun,
- Management of large sets of photographs, providing difficulties to achieve resection and successful bundle adjustment.
The experience gained in solving these problems will allow improvements in future applications of the technique. Long-range TDP has significant potential in large open-pit mine environment and on large natural slopes, where limited accessibility and rockfall hazard exist.

Concerning discontinuity characterization, the following observations are noted based on the preliminary results of this research:

i. Characterization at the pit wall scale using the \( f = 55 \) mm lens has proven useful, since it has enabled mapping to be conducted relatively quickly at reasonable detail, providing an initial view of the structure. Clearly defined, persistent structures have been mapped at this resolution and compare well to structures mapped on other focal length stereomodels. The intention is to extend the use of \( f = 400 \) mm imagery to map key areas in an attempt to improve the detail of the structure captured (Fig. A2-7).

ii. A current limitation of the photogrammetry-specific software for \( f = 400 \) mm mapping is the number of models that can be stored on screen at any one time. On high resolution stereomodels, this increases the potential for censoring of persistent planes, making it harder to establish a true trace length. Some initial work using the Maptek Vulcan code has been carried out to overcome this issue, the use of this code allowing more images to be loaded on-screen at any one time while the operator continues delineating persistent planar structures. (This limitation is considered transient and related to hardware/software issues, which will undoubtedly be alleviated in the near future.)

iii. The results of this research show that long-range TDP is able to accurately quantify discontinuity orientation, persistence and intensity. These three parameters are the main input required for the generation of discrete fracture network (DFN) models. In this preliminary application at the Palabora site, it is shown that discontinuity persistence and fracture intensity are highly dependent on the photogrammetric observation scale. Further work on the effect of observation scale on both fracture intensity and block size is ongoing.

Work to date emphasizes that it is critical that geologists and geological engineers decide at the planning stage on appropriate resolutions for the specific purposes of
their application. If only large structures need to be characterized, low ground resolution stereomodels may be sufficient, while if a more detailed characterization of rock mass fracturing is required, higher ground resolution must be achieved.

Conclusion

A significant number of stereomodels were obtained by terrestrial digital photogrammetry during approximately one full week at Palabora Open Pit. Preliminary results are presented but the volume of existing data still requires considerable processing time for both stereomodel generation and geotechnical analysis of areas of interest.

The data is also available for other TLS applications, including rock fall/bench deterioration monitoring. Indeed, subsequent surveys would provide the opportunity to quantify/record (multi)bench deformation mechanism that might be related to underground mining. Deformation monitoring using long-range TDP would be possible but would require appropriate improvements in survey control points. This would be particularly useful to track continuing underground activities related movements and to guarantee the security of the mine personal at specific locations of the pit.

Acknowledgments

All salaries, equipment and travel involved in this work were funded through an Endowment to Professor Stead, NSERC CRD and NSERC Operating Grants, an NSERC Undergraduate research scholarship (Sung Lee) and an SFU Ph.D. scholarship (Andy Beveridge). We are grateful to Palabora Mine and the geotechnical/geological staff for providing food and accommodation and the generous field support while undertaking the field work.
Figure A2-7. Long-range $f = 400$ mm TDP model imaged from 1600 m and illustrating the detailed structure within a section of the North Wall (the model contains 4 images).
Reference list


Piteau Associates Engineering Ltd., 2005. Assessment of pit wall instability and slope displacement as a result of interaction between the open pit and underground mine. Internal Report.


APPENDIX 3: SUMMARY REPORT ON TERRESTRIAL LIDAR AND PHOTOGRAMMETRY IMAGING OF TURTLE MOUNTAIN

This appendix has been written as:

Summary

Field work has been undertaken on Turtle Mountain over 3 successive campaigns, during summer 2006, 2007 and 2008. The objective was to assess the potential of terrestrial laser scanning and terrestrial digital photogrammetry for structural mapping of a large landslide. It was intended to create terrestrial DEMs at a higher ground resolution than using airborne DEMs, allowing a more detailed characterization of the steep rock slopes. Initial work with the terrestrial laser scanner highlighted important issues related to occlusion, when surveying the East face of the mountain. However, further tests with long-range terrestrial digital photogrammetry showed the potential of this technique to provide high resolution stereomodels of this inaccessible face. Based on these preliminary tests, a composite 3D model of the South Peak has been generated, combining the advantages of both techniques. Discontinuity characterization on this model provides measurements of medium- to extremely high-persistence features, which have not been documented during previous investigations. Such features could play an important role in the stability of the mountain.

Introduction

Three successive field campaigns have been conducted by the SFU Engineering Geology and Resource Geotechnics Working Group on Turtle Mountain, during the summer 2006, 2007 and 2008. The main objective was to evaluate the use of terrestrial remote sensing techniques for structural mapping of a large landslide. Each campaign
lasted between 2 and 4 days, comprising a total of 10 days in the field. Funding was provided through an NSERC Discovery grant, NSERC Equipment grants, 5 NSERC undergraduate scholarships and an FRBC Endowment awarded to the second author.

Fieldwork logistics were managed by Corey Froese and Francisco Moreno from the Alberta Geological Survey, who kindly provided helicopter access to the site slopes. The SFU Engineering Geology and Resource Geotechnics Working Group constituted of:

- M. Sturzenegger, D. Stead, M. Yan, A. Wolter and G. Patton, 5-6 June 2006,
- M. Sturzenegger, T. Sivak and R. Easterbrook, 8-11 July 2007,

This report summarizes the work achieved in the field and the results published in a conference paper and a journal paper (Sturzenegger et al., 2007; Sturzenegger and Stead, 2009b). The attached DVDs provide a database of photographs, point clouds, DGPS measurements and field observations available for further analyses. References to files and folders in the DVDs are highlighted in the report.

**Methodology**

**Terrestrial Laser Scanning (TLS)**

The laser scanner used in this project was an Optech ILRIS-3D (Optech Inc., 2008) (Fig. A3-1). It uses time-of-flight technology to determine distances of up to approximately 800 m to the rock. In order to use this scanner at the required close- and medium-ranges, it had to be transported to several locations on Turtle Mountain involving less than optimal lines of sight. As opposed to terrestrial digital photogrammetry, it is convenient for application on narrow ridges, with limited vantage points. Indeed, a single position is enough to create a point cloud of the scene. TLS data were processed using the commercial code Polyworks (InnovMetric software, 2006).
Long-range Terrestrial Digital Photogrammetry

Terrestrial digital photogrammetry (TDP) was achieved using a Canon EOS 30D digital camera with varying focal length lenses and the photographs processed using 3DM Calibcam/Analyst software (Adam Technology, 2007) (Fig. A3-2). This technique requires acquisition of photographs of the same scene from two or more vantage points, which can be impractical in rugged terrain. However, using high focal length lenses ($f = 200-400$ mm) has the advantage of allowing the creation of high resolution stereomodels of a scene at long-range ($> 1$ km). In this project, TDP was used to survey the East facing scar of the Frank Slide from Highway 3, i.e., at a range of more than 2 km.
Three-dimensional model registration is an important component of a terrestrial remote sensing project. Depending on the amount of time, effort and money available, various registration approaches can be used (Sturzenegger and Stead, 2009a and 2009b). For the Turtle Mountain project, it was decided to survey a number of large high contrast coloured targets, in addition to laser scanner/camera positions with a Differential Global Positioning System (DGPS) (Fig. A3-3). A single frequency Thales Promark3 device was used (Thales Group, 2008).

Field mapping

Field measurement of discontinuity characteristics was conducted at selected locations. Field measurement, camera, scanner and DGPS positions are displayed in shapefiles created in an ArcGIS project [DVD1 folder “ArcGIS”].
During the first field campaign, in 2006, a series of 15 trial laser scans were achieved across Turtle Mountain (Table A3-1 and Fig. A3-4). The surveyed area covered most of the upper part of the failure surface (scar) and parts of the back scar, where the tension cracks are located. From this initial survey, some conclusions and recommendations for the subsequent field campaigns could be drawn.

- TLS provides useful data when the scanner line-of-sight is not too oblique to the rock face being surveyed (Figs. A3-5 to A3-7). On Turtle Mountain, the NW, SE and to a minor extent the SW faces of the South Peak are well suited for TLS surveys. However, the E and ENE scar of the Peak cannot be optimally surveyed, because of the obliquity of the view resulting in a large amount of occlusion zones within the point clouds (Fig. A3-5).
- Despite the problem of occlusion zones, the combination of all scans listed in Table A3-1, is able to provide a global 3D model of Turtle Mountain (Fig. A3-8), from which contour maps can be generated (Fig. A3-9) \cite{DVD1 folder TLS bis/Global Turtle 2006}.

- There is a considerable potential for mapping of smaller scale features, using TLS at close- to medium-range, such as the tension cracks situated between the North Peak and South Peak (Fig. A3-10). It is recommended to achieve several scans from various TLS locations and merge the point clouds in order to create optimal 3D models.

Preliminary results of the 2006 field campaigns have been presented in Sturzenegger et al. (2007).

Table A3-1. Scan locations and ground resolutions (after Sturzenegger et al., 2007).

<table>
<thead>
<tr>
<th>Scanner location</th>
<th>Scan name</th>
<th>Ground point spacing [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Crest A</td>
<td>NCA1</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>NCA2</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>NCA3</td>
<td>26.6</td>
</tr>
<tr>
<td>North Crest B</td>
<td>NCB1</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>NCB2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>NCB3</td>
<td>90</td>
</tr>
<tr>
<td>North Peak</td>
<td>NP1</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>NP2</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>NP3</td>
<td>5.8</td>
</tr>
<tr>
<td>South Peak A</td>
<td>SPA1</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>SPA2</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>SPA3</td>
<td>4.5</td>
</tr>
<tr>
<td>South Peak B</td>
<td>SPB1</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>SPB2</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>SPB3</td>
<td>4.3</td>
</tr>
</tbody>
</table>
Figure A3-4. Map of Turtle Mountain, indicating the ground-based laser scanner positions and the area covered by ground-based laser scanning survey (Sturzenegger et al., 2007; by permission).

<table>
<thead>
<tr>
<th>Difficulty level</th>
<th>Examples/Uses</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV (highest)</td>
<td>Large scale &quot;remote&quot; inaccessible rock slides. Eg. Hope Slide.</td>
<td>Often inadequate scanner range (~1500m). Excessive elevation angle from below, azimuth bias/occlusion bias from crest. Difficult to define joint sets.</td>
</tr>
</tbody>
</table>

Figure A3-5. Locations of the laser scanner along Turtle Mountain ridges.
Figure A3-6. Point cloud (NCA2) of the South Peak scanned from the crest north of the North Peak. (a) Point cloud of the rock slope as seen from the laser scanner position, (b) point cloud of the same rock slope rotated, showing a number of occlusion zones (Sturzenegger et al., 2007; by permission).
Figure A3. 7. Point cloud (SPB2) of the North Peak scanned from the South Peak. (a) Point cloud of the rock slope as seen from the laser scanner position, (b) point cloud of the same rock slope rotated, showing a number of occlusion zones (Sturzenegger et al., 2007; by permission).
Figure A3- 8. Global point cloud combining all scans achieved on Turtle Mountain during the summer 2006.
Figure A3-9. Approximate 10 m contour map derived from the global point cloud shown in Fig. A3-8.
Figure A3-10. Point cloud (NP2) of the tension cracks to the south of the North Peak, showing details of the tension crack morphology (Sturzenegger et al., 2007; by permission).
Summer 2007

Unfortunately, a significant component of the field work in 2007 was negated by technical problems with the laser scanner and the DGPS. (Striping with the LiDAR point clouds occurred and severely compromised the images. The LiDAR was subsequently sent for service to Optech.) Consequently, 2 days of work were wasted. The survey was repeated successfully in 2008.

However, terrestrial digital photogrammetry survey of the East scar of the slide was achieved successfully using various focal length lenses ($f = 50, 100, 200$ and $400$ mm). Figure A3-11 shows a stereomodel created using an $f = 50$ mm lens of the East face of Turtle Mountain. Using larger lenses up to $f = 400$ mm, the level of detail of stereomodels increases (Fig. A3-12), with significant potential for mapping of medium-to extremely high-persistence discontinuities (ISRM, 1978) (Fig. A3-12) [DVD1 folders “TDP/frank 400mm” and “TDP/hillcrest 400mm”].
Figure A3-11. Terrestrial digital photogrammetry stereomodel of the East face of Turtle Mountain, created using an $f = 50$ mm lens.
Figure A3- 12. High resolution stereomodels ($f = 400 \text{ mm}$) of the South Peak achieved from Highway 3 (a) on the slide debris, (b) north of Hillcrest (see Fig. A3-14a).

In addition to terrestrial remote surveying, field measurements of discontinuity characteristics, including dip, dip direction and persistence, were achieved at 3 locations.
on the South Peak, complementing existing data provided by Couture (1998), Spratt and Lamb (2005) and Jaboyedoff et al. (2009) (Fig. A3-13). This database is displayed in ArcGIS shapefiles [DVD1 folder “Discontinuity/manual_joint_survey.xls” and folder “ArcGIS”] and will be used for comparison of discontinuity measurements obtained from 3D models.

![Field measurement locations, including observations provided in Couture (1998), Spratt and Lamb (2005) and Jaboyedoff et al. (2009).](image)

**Figure A3-13.** Field measurement locations, including observations provided in Couture (1998), Spratt and Lamb (2005) and Jaboyedoff et al. (2009).

**Summer 2008**

Based on experience gained during the 2006 and 2007 field seasons and summarized in the previous sections, it was decided to focus the 2008 field campaign on the generation of a composite TLS/TDP 3D model of the South Peak, combining the advantages of each technique to cover the entire peak. Eight scans and two sets of high focal length photographs \((f = 200 \text{ and } 400 \text{ mm})\) were taken from 7 locations around the South Peak and along Highway 3 (Fig. A3-14a). Eight high contrast coloured targets were surveyed with the DGPS for registration of the 3D model (Fig. A3-14b). [All data are available in the DVD1 and 2 folders “TLS”, “TDP” and file “DGPS_frank2008”].
Figure A3-14. Survey of the South Peak. (a) Map of the mountain with the locations of the TDP (black dots) and the TLS (black stars) (Sturzenegger and Stead, 2009b), (b) photograph of the South Peak with 3 high contrast pink targets.
3D model generation

This section summarizes the composite 3D model (terrestrial DEM) generation and quality assessment. This topic has been presented in Sturzenegger and Stead (2009b). The model has been created by merging both TLS and TDP data using the software Polyworks. [The terrestrial DEM is on the DVD1 folder “Terrestrial DEM South Peak/southpeak_terrDEM”].

DGPS survey accuracy

The DGPS base station was located on the benchmarks “AltaEnv 1985 1” of the South Peak and “ASCM 58032” near the Interpretive Centre. Measurement accuracy was verified using the “ASCM 66T” benchmark located on the Third Peak. At this location, the difference between surveyed and existing coordinates has been calculated. Table A3-2 shows that the horizontal accuracy is on average 4.5 cm and the vertical accuracy ranges between 5 mm and 1 m [DVD1 file “DGPS_frank2008.xls”].

Table A3-2. DGPS survey accuracy.

<table>
<thead>
<tr>
<th>ASCM 66T benchmark</th>
<th>Δ horizontal [m]</th>
<th>Δ vertical [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>0.047</td>
<td>-0.005</td>
</tr>
<tr>
<td>Day 2</td>
<td>0.043</td>
<td>1.007</td>
</tr>
</tbody>
</table>

3D model quality

A 3D model is defined as a point cloud containing hundreds of thousands to millions of three dimensional data (x, y and z independent coordinates). In addition, each data contains information about the object surface reflectivity and/or color. 3D models do not always represent bare Earth, since vegetation and other objects can sometimes only partly be filtered.

The accuracy and precision of the composite 3D model is detailed in Table A3-3, estimated by comparison with the DGPS survey [complete data in DVD1 file “composite_model_accuracy.xls”]. Several parameters contribute to the overall model
error, including the inherent accuracy of the laser scanner, the stereomodel creation process, alignment of successive models and target recognition. The main error component in the current project resulted from the alignment process, as the challenging mountainous terrain sometimes made it impossible to obtain optimal overlap between successive adjacent models.

The quality of the composite 3D model was evaluated by overlaying and comparing with an airborne LiDAR DEM, provided by Corey Froese (AGS). To accomplish this, the shortest distance between each point on the 3D model and the reference airborne LiDAR DEM were computed and displayed as an error map. Figure A3-15b shows that, with the exception of a few limited areas, the two models match very well (errors up to 2-3 m). Locally, errors up to 5 metres occur due to scattered large boulders, gullies and trees, which could not be filtered out.

The terrestrial composite 3D model has a higher ground resolution than the airborne LiDAR DEM, but is frequently affected by occlusion zones at the very top of the peak, behind trees and protruding blocks, or along cracks and gullies (Fig. A3-15a). Depending on access, these occluded areas could, in the future, be mapped in more detail, using close-range TDP or TLS surveys.

Table A3-3. Accuracy (mean error) and precision (standard deviation) of the composite 3D model of the South Peak (Sturzenegger and Stead, 2009b).

<table>
<thead>
<tr>
<th></th>
<th>Northing</th>
<th>Easting</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean error [m]</td>
<td>0.141</td>
<td>-0.057</td>
<td>-0.084</td>
</tr>
<tr>
<td>Standard deviation [m]</td>
<td>0.490</td>
<td>0.603</td>
<td>1.224</td>
</tr>
</tbody>
</table>
Figure A3-15. Composite 3D model of the South Peak. (a) Oblique view of the NE side, displayed using ArcScene, (b) plane view of the error map of the whole model (Sturzenegger and Stead, 2009b).
Discontinuity characterization

The following section is presented from Sturzenegger and Stead (2009b). A major advantage of the terrestrial 3D model is that it allows recognition of medium- and higher-persistence discontinuities located on oblique to sub-vertical rock slopes, such as the failure surface and lateral boundaries of the slide, where airborne LiDAR DEM resolution is in contrast more limited.

Discontinuity characterization covers the upper part of the South Peak above an elevation of 2000 m, in the Livingstone Formation (Figs. A3-16 and A3-17) [DVD1 folder “Discontinuity” and folder “TDP/frank 400mm, DVD2 folder “TLS/summer 2008/Polyworks scanner data/Southpeak_mapping.pwk]. Discontinuity position, orientation and persistence are provided in the DVD1 [folder “Discontinuity]. Figure A3-18a shows that bedding planes are clearly recognized and that cross joints have a large variability in orientation. Figure A3-18b shows that most discontinuities smaller than about 2 m cannot be recognized and that consequently medium- to extremely high persistence structures were mapped (Table A3-4). Discontinuity sets J1 and J2 described by Couture (1998) and Spratt and Lamb (2005) can be recognized. S0, J2 and J4 sets were mapped by Brideau (M.-A. Brideau, personal communication, 2008).

Discontinuity set J3 has been mapped both in the field by Brideau, and on airborne DEM by Jaboyedoff et al. (2009). However, J3 obtained from terrestrial 3D models is slightly different (higher dip value) from the one recognized by the previous authors. Two possible reasons may explain this; firstly, discontinuity set J3 was mapped on the East facing scar of the South Peak, where there is very limited access for field mapping. In addition, Fig. A3-18c shows that most of the J3 discontinuities are very high- to extremely high-persistence surfaces (Table A3-4). It is possible that these surfaces represent composite surfaces, similar to the one shown in Fig. A3-19, which combines both joints and intact rock fractures with a step-path geometry (Sturzenegger and Stead, 2009b). Such features are not observed during field observations, which focus on lower persistence joints.
Table A3-4. Persistence classes (modified after ISRM, 1978).

<table>
<thead>
<tr>
<th>Class</th>
<th>Persistence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>&lt; 1 m</td>
</tr>
<tr>
<td>Low</td>
<td>1 – 3 m</td>
</tr>
<tr>
<td>Medium</td>
<td>3 – 10 m</td>
</tr>
<tr>
<td>High</td>
<td>10 – 20 m</td>
</tr>
<tr>
<td>Very high</td>
<td>20 – 40 m</td>
</tr>
<tr>
<td>Extremely high</td>
<td>&gt; 40 m</td>
</tr>
</tbody>
</table>

Figure A3-16. Discontinuity characterization on South Peak, using TLS point clouds and the software Polyworks.
Figure A3-17. Discontinuity characterization on the East face of South Peak, using TDP stereomodels and the software 3DM Analyst.
Figure A3-18. Discontinuity characterization. (a) Stereonet (lower hemisphere, equal area projection, first contour=3%, interval=2% per 1% area), (b) equivalent trace length distribution, (c) symbolic pole plot of persistence class (Sturzenegger and Stead, 2009b).
Figure A3-19. Example of composite surface, combining both joints and intact rock fractures with a step-path geometry (after Sturzenegger and Stead, 2009b).

Mapping a large landslide using terrestrial remote sensing techniques

This project on Turtle Mountain highlighted the potential of terrestrial remote sensing techniques for structural characterization of a large landslide. It showed that:

- Both long-range terrestrial digital photogrammetry and terrestrial laser scanning allow the creation of high resolution 3D models (up to 40 mm and 96 mm ground point spacing for TLS and TDP, respectively) of steep rock slopes. Such slopes are difficult to survey using airborne techniques, resulting in a lack of useful information.
- Long-range TDP and TLS complement each other and their combination allows one to minimize problems due to occlusion, when the scanner line-of-sight is too oblique with respect to rock slope. TLS is convenient on sharp ridges, where accessibility and rapid changes in perspective limit the use of TDP (which require two or more camera stations). TDP allows building high resolution stereomodels at a range exceeding
2km, when a large focal length \((f = 200-400 \text{ mm})\) lenses is used. The accuracy of 3D models was found to be good.

- Mapping on the 3D model of the South Peak highlights the potential for characterization of medium- to extremely high-persistence discontinuities. Some steep discontinuities have been recognized, which have not been observed in previous investigations. It is possible that they represent step-path features, which combine several discontinuity sets and include intact rock fractures. Such features could have played an important role in the generation of the Frank Slide failure surface.

**Reference list**


Sturzenegger, M., Stead, D., 2009b. Quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial remote sensing techniques. Natural Hazards and Earth System Sciences 9, 267-287.


APPENDIX 4: ROCK SLOPE REMOTE SENSING 3D MODELS DATABASE

Table A4-1 summarizes all rock slope TLS/TDP 3D models created using terrestrial laser scanning or terrestrial digital photogrammetry. Most of them have been used in the current research and some others have been or will be incorporated in other research projects. In order to provide a comprehensive database, some 3D models surveyed by Ming Yan, Alex Strouth, Dave VanZeyl and George Patton have been included.
Table A4-1. Terrestrial remote sensing data collected and conventional field surveys achieved.

<table>
<thead>
<tr>
<th>Place</th>
<th>Date</th>
<th>Terrestrial remote sensing technique</th>
<th>Rock type</th>
<th>Registration</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aberdeen Hwy. (Washington)</td>
<td>2005</td>
<td>5 scans (close-range)</td>
<td>Sandstone</td>
<td>Approach A</td>
<td>Scans done by Ming Yan and Doug Stead</td>
</tr>
<tr>
<td>Barrier (Garibaldi Provincial Park – BC)</td>
<td>October 2008</td>
<td>105 photographs (medium-range, $f$ = 50, 100 or 200 mm)</td>
<td>Dacite lava</td>
<td>Approach B (DGPS)</td>
<td>For Peter Schön Master’s project</td>
</tr>
<tr>
<td>BC Rail Quarry (Hwy. 99 - BC)</td>
<td>May 2006</td>
<td>2 scans (close-range)</td>
<td>Columnar basalt</td>
<td>Approach A</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Bingham Canyon open-pit mine (Utah)</td>
<td>September 2006</td>
<td>21 scans (close-range)</td>
<td>Sandstone, limestone, monzonite</td>
<td>TLS: approach A</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>34 photographs (close-range, $f$ = 50 mm)</td>
<td></td>
<td>TDP: approach D (DGPS)</td>
<td></td>
</tr>
<tr>
<td>Boston Bar (Hwy. 1 - BC)</td>
<td>June 2006</td>
<td>5 scans (close-range)</td>
<td>Pelites, siltstones and tuffs</td>
<td>Approach A</td>
<td>Scans done by George Patton</td>
</tr>
<tr>
<td>Bridal Veil Falls (Banff National Park - Alberta)</td>
<td>July 2007</td>
<td>6 scans (medium-range)</td>
<td>Limestone (Palliser Formation)</td>
<td>TLS: approaches A and C (total station)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>133 photographs (medium-range, $f$ = 50, 100, 200 and 400 mm)</td>
<td></td>
<td>TDP: approaches B and C (total station)</td>
<td></td>
</tr>
<tr>
<td>Place</td>
<td>Date</td>
<td>Terrestrial remote sensing technique</td>
<td>Rock type</td>
<td>Registration</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------------------------</td>
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<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Chehalis Lake Rockslide (Coast Mountain – BC)</td>
<td>May 2009</td>
<td>135 photographs (medium and long-range, $f = 50, 100, 200 and 400$ mm)</td>
<td>Quartz diorite</td>
<td>Pre-registered airborne LiDAR DEM</td>
<td>For Marc-André Brideau’s Ph.D. project</td>
</tr>
<tr>
<td>Chief (Squamish – BC)</td>
<td>October 2005</td>
<td>15 scans (close-range)</td>
<td>Granodiorite (Coast Plutonic Complex)</td>
<td>TLS: approach A TDP: n/a</td>
<td>Scans done by Dave VanZeyl</td>
</tr>
<tr>
<td>Cirrus Wall (Banff National Park - Alberta)</td>
<td>September 2006</td>
<td>3 scans (medium-range)</td>
<td>Limestone (Palliser Formation)</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Crowsnest Lake (Hwy. 3 – Alberta)</td>
<td>June 2008</td>
<td>2 scans (close-range)</td>
<td>Limestone</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Cultus Lake (Chilliwack - BC)</td>
<td>January 2006</td>
<td>7 scans (close-range)</td>
<td>Meta-sediments (Cultus Formation)</td>
<td>Approach A</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Elk Valley mine (BC)</td>
<td>July 2007</td>
<td>10 scans (close- and medium-range)</td>
<td>Coal (Kootenay Group)</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Jasper roadcut (Jasper - BC)</td>
<td>September 2006</td>
<td>8 scans (close-range)</td>
<td>Sandstone, conglomerates, slates and schists (Wynd Formation)</td>
<td>TLS: approach A TDP: approach D (DGPS)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Place</td>
<td>Date</td>
<td>Terrestrial remote sensing technique</td>
<td>Rock type</td>
<td>Registration</td>
<td>Comments</td>
</tr>
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<tr>
<td>Kicking Horse Canyon (Golden - BC)</td>
<td>September 2006</td>
<td>4 scans (close-range) 18 photographs (close-range, ( f = 50 ) mm)</td>
<td>Dolomite</td>
<td>TLS: approach A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TDP: approach D (DGPS)</td>
<td></td>
</tr>
<tr>
<td>Lake Louise road cut (Hwy 1 – Alberta)</td>
<td>June 2006, September 2006 and July 2007</td>
<td>13 scans 90 photographs (close-range, ( f = 50 ) mm)</td>
<td>Silty slate units (Miette Group)</td>
<td>TLS: approaches A and C(total station) TDP: approaches A, B, C, D and E (total station)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Manning Park (Hwy 3 - BC)</td>
<td>July 2006</td>
<td>4 scans (close-range) 24 photographs (close-range, ( f = 50 ) mm)</td>
<td>Slate with lenses of sandstone (Jackass Mountain Group)</td>
<td>Approach D (DGPS)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Marine Drive (Vancouver – BC)</td>
<td>March 2007, 2008 and 2009</td>
<td>5 scans (close-range) 24 photographs (close-range, ( f = 50 ) mm)</td>
<td>Quartzite</td>
<td>TLS: approach A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TDP: approach D (DGPS)</td>
<td></td>
</tr>
<tr>
<td>Medicine Lake roadcut (Jasper National Park – Alberta)</td>
<td>September 2006</td>
<td>6 scans (close-range)</td>
<td>Limestone (Palliser Formation)</td>
<td>Approach A</td>
<td>Scans done by Ming Yan</td>
</tr>
<tr>
<td>Place</td>
<td>Date</td>
<td>Terrestrial remote sensing technique</td>
<td>Rock type</td>
<td>Registration</td>
<td>Comments</td>
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<tr>
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<tr>
<td>Medicine Lake Rockslide (Jasper National Park – Alberta)</td>
<td>July 2007</td>
<td>43 photographs (long-range, $f = 50, 100, 200$ and 400 mm)</td>
<td>Limestone (Palliser Formation)</td>
<td>Approach D (DGPS)</td>
<td></td>
</tr>
<tr>
<td>Mount Edith Cavell (Jasper National Park – Alberta)</td>
<td>July 2007 and 2008</td>
<td>7 scans (medium-range) 177 photographs (medium-range, $f = 20, 50, 100, 200$ and 400 mm)</td>
<td>Quartzite (Gog Group)</td>
<td>TLS: approaches A and C (total station) TDP: approaches B and C (total station)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Mount Seymour (Vancouver – BC)</td>
<td>June and October 2007</td>
<td>13 scans (close-range) 256 photographs (close-range, $f = 50$ mm)</td>
<td>Quartz dorite (Coast Plutonic Complex)</td>
<td>TLS: approaches A and C (total station) TDP: approaches A, B, C, D, E (total station and DGPS)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Murrin Lake (Hwy. 99 – BC)</td>
<td>February and July 2006</td>
<td>4 scans (close-range) 8 photographs (close-range, $f = 50$ mm)</td>
<td>Granodiorite (Coast Plutonic Complex)</td>
<td>TLS: approach A TDP: approach D (DGPS)</td>
<td></td>
</tr>
<tr>
<td>NewHalem (Afternoon Creek Slide - Washington)</td>
<td>2005</td>
<td>16 scans (medium-range)</td>
<td>Orthogneiss</td>
<td>Approach A</td>
<td>Scans done by Ming Yan and Alex Strouth</td>
</tr>
<tr>
<td>Place</td>
<td>Date</td>
<td>Terrestrial remote sensing technique</td>
<td>Rock type</td>
<td>Registration</td>
<td>Comments</td>
</tr>
<tr>
<td>-------------------------------------------</td>
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</tr>
<tr>
<td>Oliver (BC)</td>
<td>June 2006</td>
<td>6 scans (medium-range)</td>
<td>Gneiss</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Othello Tunnels (Hope – BC)</td>
<td>August 2007 and June 2009</td>
<td>8 scans (close-range) 24 photographs (close-range, f = 20 mm)</td>
<td>Granodiorite</td>
<td>Approach A</td>
<td>Underground photogrammetry test</td>
</tr>
<tr>
<td>Palabora Open Pit Mine (South Africa)</td>
<td>February 2008</td>
<td>32 scans (close- and medium-range) 2251 photographs (close- to long-range, f = 20, 50, 55, 100, 200 and 400 mm)</td>
<td>Various intrusive rocks into Archean granite</td>
<td>TLS: approach A TDP: approach C (DGPS)</td>
<td></td>
</tr>
<tr>
<td>Palliser Rockslide (Peter Lougheed Provincial Park – Alberta)</td>
<td>June 2008</td>
<td>611 photographs (medium/long-range, f = 20, 50, 200 and 400 mm)</td>
<td>Limestone (Upper Banff Formation)</td>
<td>Approach C (DGPS)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Penticton (BC)</td>
<td>June 2006</td>
<td>15 scans (close-range)</td>
<td>Gneiss</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Porteau Cove (Hwy. 99 – BC)</td>
<td>July 2006 and October 2007</td>
<td>19 scans (close- and medium-range) 179 photographs (close- and medium-range, f = 20, 50 and 100 mm)</td>
<td>Quartz diorite (Coast Plutonic Complex)</td>
<td>TLS: approach A TDP: approach D (DGPS)</td>
<td>Part of the scans done by Ming Yan</td>
</tr>
<tr>
<td>Place</td>
<td>Date</td>
<td>Terrestrial remote sensing technique</td>
<td>Rock type</td>
<td>Registration</td>
<td>Comments</td>
</tr>
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</tr>
<tr>
<td>Saskatchewan Crossing (Banff National Park – Alberta)</td>
<td>September 2006 and July 2007</td>
<td>17 scans (close-range) 122 photographs (close-range, ( f = 50 ) mm)</td>
<td>Limestone (Eldon Formation)</td>
<td>TLS: approaches A and C (total station) TDP: approaches A, B, C, D, E (total station)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Simon Fraser University (TASC 1 building - BC)</td>
<td>June 2008</td>
<td>22 scans (close-range)</td>
<td>(concrete)</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Three Valley Gap (Hwy. 1 – BC)</td>
<td>June 2006</td>
<td>3 scans (medium-range)</td>
<td>Gneiss</td>
<td>Approach A</td>
<td></td>
</tr>
<tr>
<td>Turtle Mountain (Frank Slide - Alberta)</td>
<td>June 2006 and 2008</td>
<td>17 scans (medium-range) 97 photographs (long-range, ( f = 50, 100, 200 ) and 400 mm)</td>
<td>Limestone (Livingstone Formation)</td>
<td>TLS: approaches A, B and C (DGPS) TDP: approaches B and C (DGPS)</td>
<td>Discontinuity field survey available</td>
</tr>
<tr>
<td>Weeping wall (Banff National Park - Alberta)</td>
<td>September 2006</td>
<td>2 scans (medium-range)</td>
<td>Limestone (Palliser Formation)</td>
<td>Approach A</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 5: COMPREHENSIVE LIST OF PUBLICATIONS RELEASED DURING THE DOCTORAL PROGRAM

Refereed journal articles


Sturzenegger, M., Stead, D., 2009b. Quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial remote sensing techniques. Natural Hazards and Earth System Sciences 9, 267-287.


Sturzenegger, M., Stead, D. Incorporation of terrestrial digital photogrammetry into the investigation of the Palliser Rockslide. To be submitted.


Peer-reviewed conference papers


**Non-reviewed publications**


**Technical reports**


