GÉORISQUES IV GEOHAZARDS

THE 1999 CLANWILLIAM LANDSLIDE: A PRELIMINARY ANALYSIS OF POTENTIAL FAILURE MECHANISMS

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RÉSUMÉ

L'éboulement Clanwilliam s'est produit le 2 avril 1999 sur le versant sud au-dessus du Lac Clanwilliam, quelques 13 kilomètres à l'ouest de Revelstoke, C.-B. L'éboulement est situé près de la marge ouest du complexe métamorphique Shuswap et d'une structure tectonique majeure, le décollement Monashee. La masse détachée est composée de roche gneissique. Une faille normale et l'axe d'un synforme ont été cartographiés à moins de 500 mètres de la zone d'initiation. Une analyse des données séismiques indique qu'aucune activité ne fut enregistrée au moment de l'éboulement. Les données météorologiques montrent qu'un cycle de gel-dégel prononcé survenus quelques jours avant la rupture ait pu jouer un rôle lors de son initiation. Des données préliminaires provenant de levés géologiques dans la zone de départ, incluant des descriptions des discontinuités et de la masse rocheuse, sont également présentées dans cet article, Ces données furent utilisées dans une analyse cinématique préliminaire afin d'identifier les mécanismes ou modes de rupture potentiels. Ceci fut suivit d'une analyse d'équilibre limite pour les dièdres utilisant des approches à la fois conventionnelle déterministique et de combinaison. L'analyse par la théorie des blocs clefs a permis d'identifier les blocs critiques et leurs géométries au sein de la masse rocheuse du glissement de terrain. Une fois la cinématique du versant étudiée, les résultats de cette étude furent utilisés pour réaliser une analyse préliminaire tridimensionnelle par éléments distincts.

ABSTRACT

The Clanwilliam Landslide, April 2nd 1999, occurred on a south facing slope above Clanwilliam Lake, approximately 13 km west of Revelstoke, B.C. The landslide is located near the western margin of the Shuswap Metamorphic Complex and a major tectonic structure known as the Monashee Decollement. The failed mass is comprised of gneissic material. A large normal fault and synform axis have been mapped within 500 metres of the landslide initiation zone. A review of the published records shows that no earthquake events were recorded prior to the failure. The climatic record showed that pronounced freeze-thaw cycles occurred the day before and on the day of the failure. Preliminary discontinuity surveys and rock mass descriptions data on the source zone of the landslide are presented. These measurements were used to perform a preliminary kinematic analysis in order to identify potential slope failure mechanisms. This was followed by limit equilibrium wedge analysis using both a conventional deterministic and a combination analysis approach. Block theory analysis was undertaken in order to identify critical blocks and block shapes within the landslide rock mass. Having investigated the kinematics of the rock slope the results of this study were used to perform a preliminary 3D-distinct element analysis.

1. INTRODUCTION

The Clanwilliam Landslide occurred on April 2nd 1999, 13 km west of Revelstoke (Fig. 1). The slope failure occurred on south facing side of the valley which is also where the rail bed for the Canadian Pacific Railway is located. The damage to the railway was minimized by a short tunnel which encompassed most of the landslide runout path width (Fig. 2). The Trans-Canada Highway is located on the opposite side of the valley and did not suffer any damage. The runout from this landslide has previously been described briefly by Ayotte and Hungr (2000) the landslide being referred to as Shuswap Mile 9.5 and by Hungr and Evans (2004) where the failure was referred to as the Eagle Pass Landslide. This article concentrates on the initiation zone of the landslide and in particular on potential trigger mechanisms.

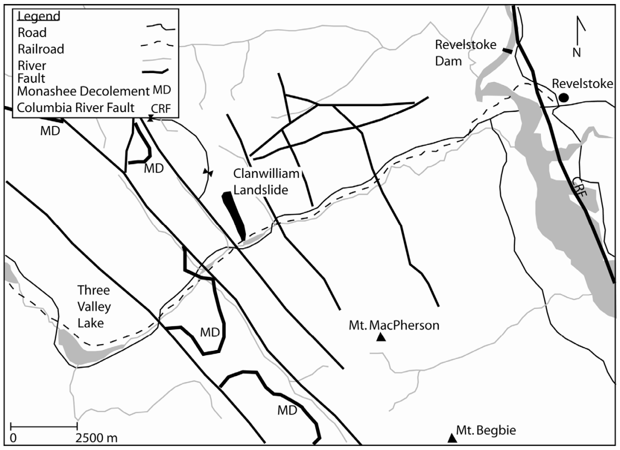

Figure 1: Location and simplified structural geology map of the Clanwilliam Landslide near Revelstoke BC (approximate fault and synform locations from Hill, 1975; Bosdachin, 1989; Harrap, 1990; Johnson, 1990, 2006).

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Comptes rendus de la 4e Conférence canadienne sur les géorisques: des causes à la gestion.
Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

Figure 2: Overview of the Clanwilliam Landslide (Photograph from 1999)

2. REGIONAL SETTING

The Clanwilliam Landslide is located near the western margin of the Shuswap Metamorphic Complex and a major tectonic structure known as the Monashee Decollement. The regional and structural geology of the surrounding area has consequently been investigated by several researchers (Jones, 1959; Hill, 1975; Bosdachin and Harrap, 1988; Bosdachin, 1989; Harrap, 1990; Johnson, 1990, 2006). The bedrock geology is mapped as "kyanite/sillimanite pelitic schist, with minor quartzo-feldspathic gneiss, calc-silicate gneiss, marble and discontent garnet hornblende gneiss" (Bodachin, 1989). A normal fault and synform axis were mapped within 500 metres of the initiation zone of the landslide (Hill, 1975; Bosdachin, 1989).

The valley bottoms and sides in this region of British Columbia are defined as part of the Interior Cedar-Hemlock (ICH) biogeoclimatic zone while the higher section and tops of the mountains are part of the Engelmann Spruce-Subalpine Fir (ESSF) zone (Meidinger and Pojar, 1991). The ICH zone is characterized by an interior continental climate, resulting in cool wet winters and warm dry summer (Meidinger and Pojar, 1991). The average temperature and precipitation for the month of March and early April as recorded at Revelstoke is presented in Table 1 (Environment Canada, 2007). Figure 3 presents the temperature and precipitation data recorded at the Clanwilliam Lake weather station two weeks prior to the failure. The Clanwilliam Lake weather station is operated by the BC Ministry of Transportation and Highway and in 1999 the data was manually collected twice a day. The morning and afternoon temperature measurements were used as proxy for the daily minimum and maximum respectively.

Table 1: Average weather conditions at the Revelstoke Airport for the months of March and April.

Month	Average daily temp. (^oC)	Minimum daily temp. (^oC)	Maximum daily temp. (^oC)	Average monthly precip. (mm)
March	1.8	-2.7	6.3	65.8
April	7.3	1.2	13.4	55.4

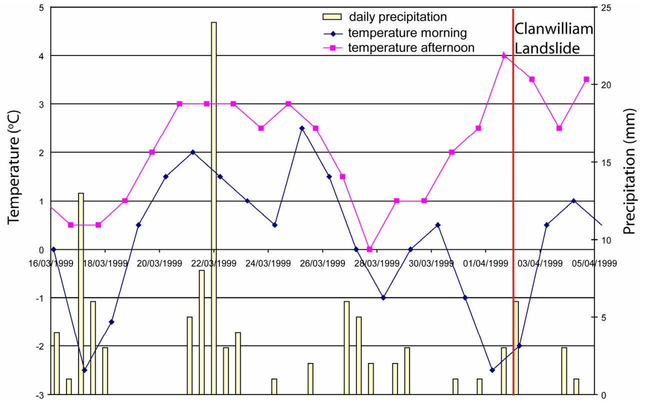

Figure 3: Temperature and precipitation data from weather station at Clanwilliam Lake two weeks prior to the landslide

3. DESCRIPTION OF THE INITIATION ZONE

Discontinuity measurements and rock mass descriptions were obtained from the headscarp area at the Clanwilliam Landslide during three 1-day visits in 1999, 2003, and 2006. Four discontinuity sets were identified (Table 2 and Fig. 4). Their orientation and characteristics are summarised in Table 2. The spacing of the discontinuities varied between close (60-200mm) and wide (600-2000mm) according to the classes established by the ISRM (1978). The surface of discontinuity sets (D.S.) 1, 2, and 3 was characterised as planar/undulating and rough. D.S. 1 and 2 represent extensional fracturing while D.S. 3 is parallel to the gneissic foliation and represents shear fracturing involved in flexural folding. Discontinuity set 4 was found to be planar and slickensided with a limited dip and strike persistence. The presence of slickensides on D.S. 4 suggests that might represent fracturing associated with the regional faulting fabric. A fifth weak concentration was also noted with a dip of 60^o and a dip direction of 032^o. The rock mass quality at the headscarp area was characterized by a Geological Strength Index (GSI) range of 40-50 which corresponds to a very blocky rock mass with a good to fair surface condition (Hoek and Brown, 1997; Marinos *et al.*, 2005). The rock samples tested in the field required several blows to break which indicates a rock strength of R5 (100-200 MPa). The rock mass was only slightly weathered (WII) with a discoloration of the rock and discontinuity surface. The block shape was observed to vary between columnar to tabular.

Table 2: Major discontinuity sets identified at the Clanwilliam Landslide

	D.S. 1	D.S. 2	D.S. 3	D.S 4
Dip (°)	64	69	38	50
Dip direction (°)	134	182	228	073
Primary roughness	Planar	Undulating	Planar	Planar
Secondary roughness	Rough	Rough	Rough	Slicken-sided
Spacing (mm)	60-200 200-600	200-600 600-2000	60-200 200-600	600-2000
Dip persistence (m)	1-3 3-10 10-20	1-3 3-10	3-10 10-20 >20	1-3
Strike persistence (m)	3-10 10-20 >20	1-3 10-20	1-3	1-3

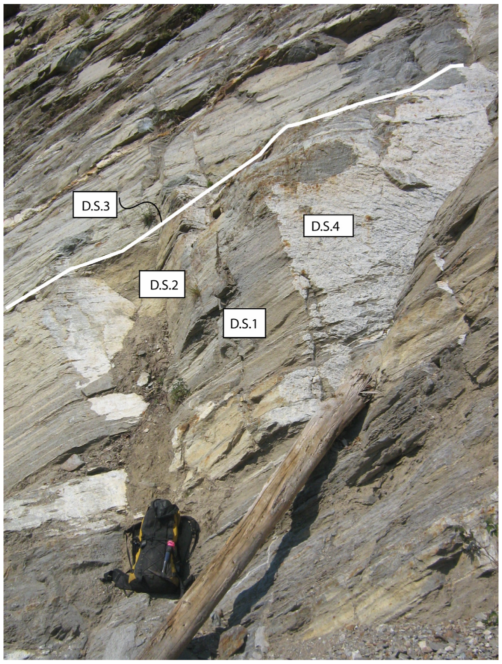

Figure 4: Close-up of the rockmass in the headscarp of the Clanwilliam Landslide highlighting the four major discontinuity sets identified.

4. ANALYSIS OF POTENTIAL FAILURE MECHANISMS

4.1 Kinematic Analysis

A kinematic analysis takes into account the geometry of the discontinuities, the slope orientation and the friction angle along the discontinuity surfaces in order to determine the potential for planar, wedge and toppling failures. These analyses are conducted using stereographic techniques. The procedures for each failure mechanism are described in Richards *et al.*, (1978), Hoek and Bray (1981) and Lisle (2004). Discontinuity measurements were collected by the first and third authors from the headscarp area (N=61). The discontinuity sets presented in Table 2 were used to perform a preliminary kinematic analysis. The results of this analysis suggested that none of the simple failure modes (planar sliding, wedge, toppling) appear to be feasible (Fig., 5).

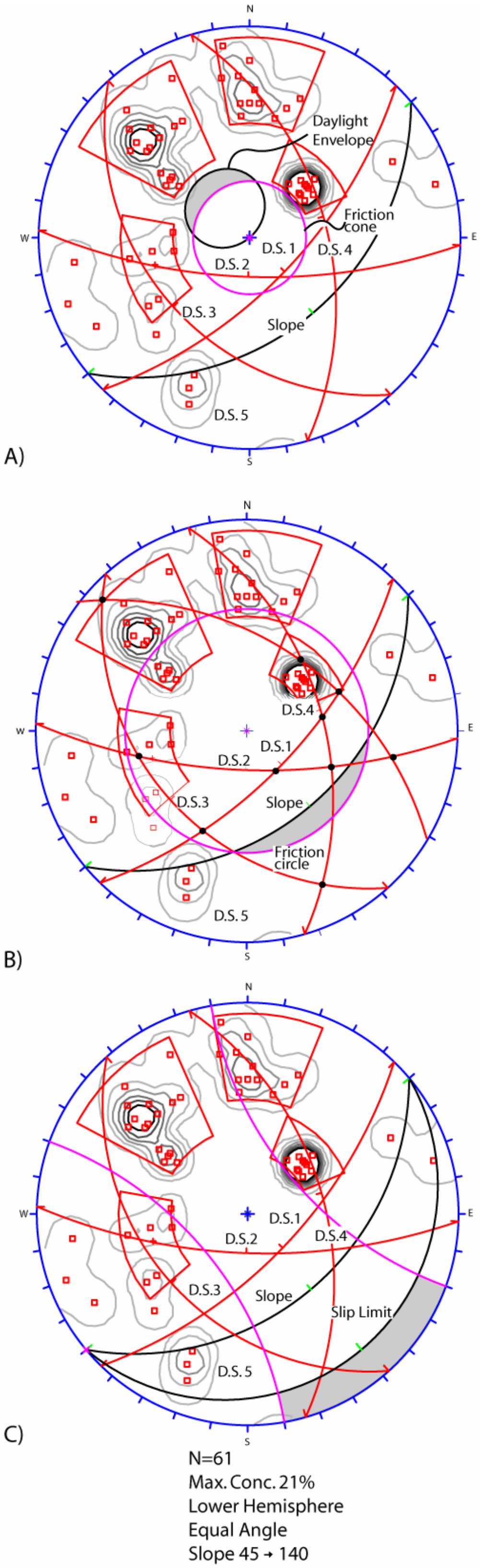

Figure 5: Kinematic analysis performed for the A) planar, B) wedge and C) toppling failure modes.

However it is recognised that a wedge failure from the intersection of D.S. 2 and D.S. 4 is nearly feasible and should be considered due to the natural variation in slope and discontinuity orientations.

4.2 Wedge analysis

Swedge is a limit equilibrium code from Rocscience (2006) which analyses the geometry and stability of surface wedges in rock slopes. The wedges are defined by two discontinuities and the slope surface. A tension crack can be added to form the rear release surface. For this paper the deterministic and combination analyses were used (Rocscience, 2006). The deterministic approach calculates the factor of safety for a set of two discontinuities, slope surface orientation and assumes shear strength along the discontinuities. The deterministic approach using the discontinuity sets presented in Table 2 indicated stable geometries. In the combination approach all the discontinuity measurements are imported in Swedge and all the possible combinations of two discontinuities and the slope surface that form a valid wedge are analyzed. Using the data collected at the Clanwilliam Landslide 392 valid wedges were formed and using a friction angle of 30^o along the discontinuities, twenty wedges had a factor of safety below 1. The distribution of the factors of safety between 0 and 5 are presented in Figure 6. Representative wedge shapes are presented in Figure 7. All the modeled wedges with a factor of safety of less than 2 had a weight of less than 5000 tons.

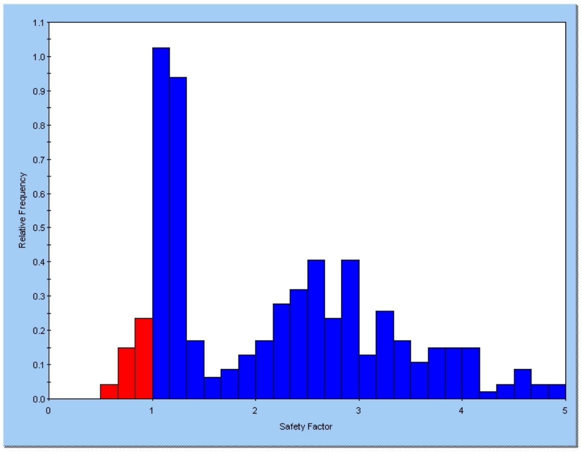

Figure 6: Histogram of the factor of safety obtained from the combination analysis performed in Swedge. Note that the data was truncated for factors of safety above 5.

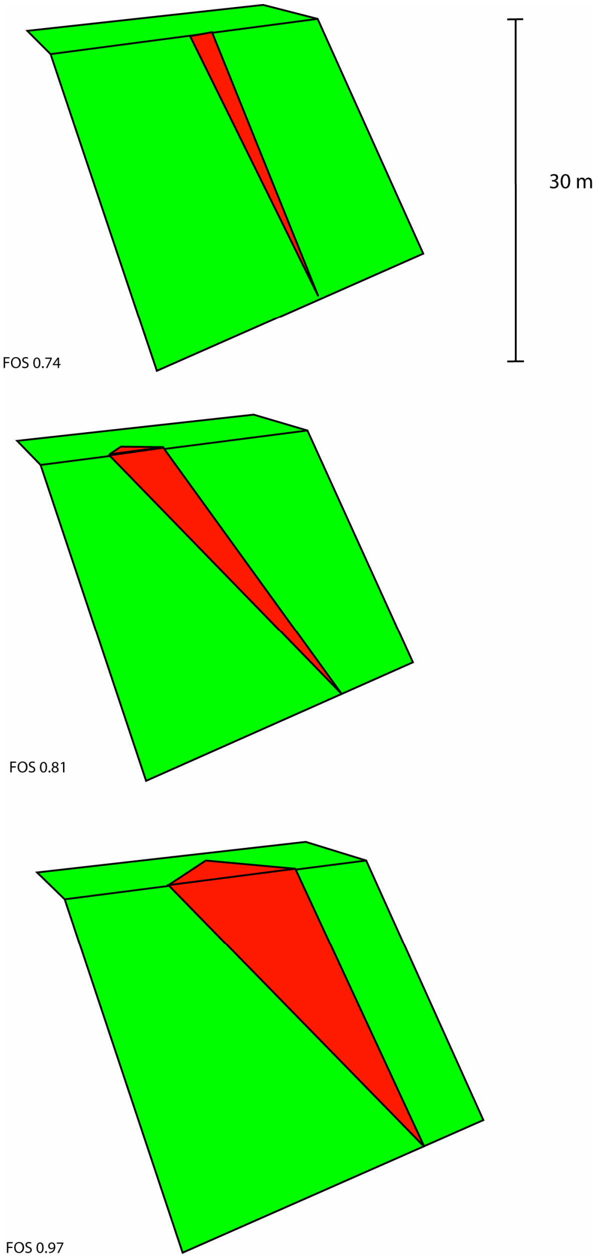

Figure 7: Typical wedge shapes with a factor of safety less than 1 obtained from the combination analysis performed in Swedge.

4.3 Block theory

Block theory considers the geometry of the discontinuities and the slope orientation in a similar manner to the kinematic analysis. In addition it determines the finiteness of blocks bounded by several discontinuities and an excavation surface along with their removability. Figure 8 shows a 2-dimensional illustration of the five block categories considered in block theory. Keyblocks are finite and removable blocks which once they have moved allow other blocks which were previously finite but non-removable the kinematic freedom to move. Block theory was developed by Goodman and Shi (1985) and it can be applied to stereographic methods (Goodman and Shi, 1985 and Priest, 1985). Goodman and Shi use the upper hemisphere stereographic projection in their analysis.

Block theory graphical methods coupled with limit equilibrium techniques have been included in computer codes such as Kbslope (Pantechnica, 2002), the code used in this paper. A block theory analysis was performed using the same discontinuity sets outlined in Table 2 and the results indicated 2 tapered and non-removable blocks, 2 removable but stable blocks and 1 block which was removable and stable only with friction angles of 30^o along the discontinuity (Figure 9). The block shape for the removable but stable with friction block created by this geometry is presented in Figure 10.

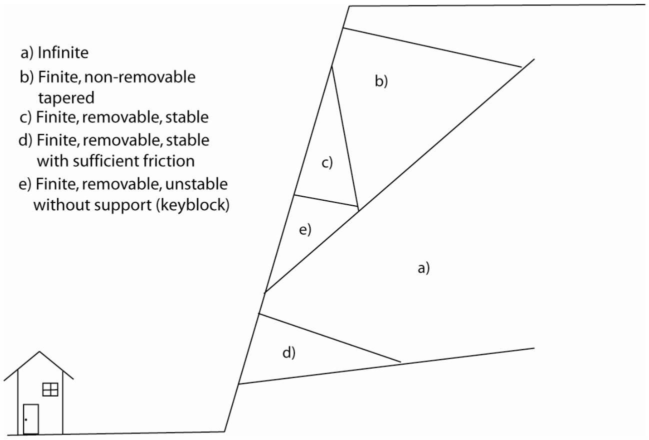

Figure 8: Finiteness and removability classes in the block theory (modified from Kulatilake *et al.*, 2003).

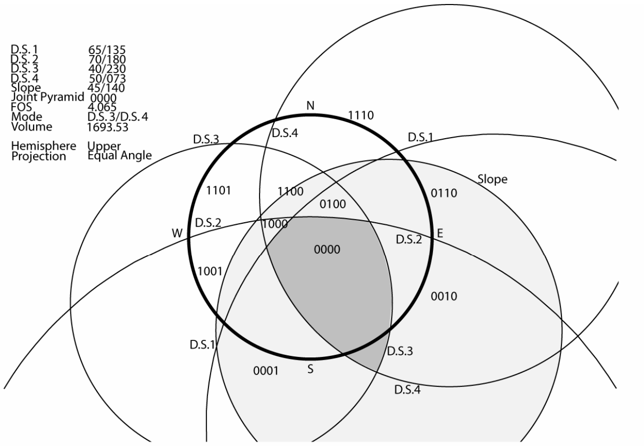

Figure 9: Upper hemisphere stereographic projection of block pyramids from the block theory for the Clanwilliam Landslide.

4.4 3-Dimensional Distinct Element Modelling

A three-dimensional distinct element code (3DEC; Itasca, 2007) was used to investigate the geometrical controls on block toppling. The code simulates the response of a discontinuum material (such as a jointed rock mass) to static or dynamic loading. The material is represented as a collection of 3D blocks. Rigid or deformable stress-strain constitutive criteria can be specified for the material making up the blocks.

Deformable blocks are meshed using finite difference elements. The discontinuities which bound the blocks are treated as boundary conditions along which large displacements and rotation are permitted. Different representations of the shear strength along these discontinuities can be specified by the user. 3DEC uses an explicit time-stepping scheme to solve the equations of motion. More details on the distinct element code can be found in Cundall (1985), Hart *et al.*, (1985) and in the "Theory and Background" manuals (Itasca, 2007). 3DEC has been used in a few case studies and in conceptual models to evaluate the stability of rock slopes (e.g. Alfonsi *et al.*, 1999; Corkum and Martin, 2004; Stead *et al.*, 2005) and has shown great potential in the investigation of failure mechanisms in 3-dimensions.

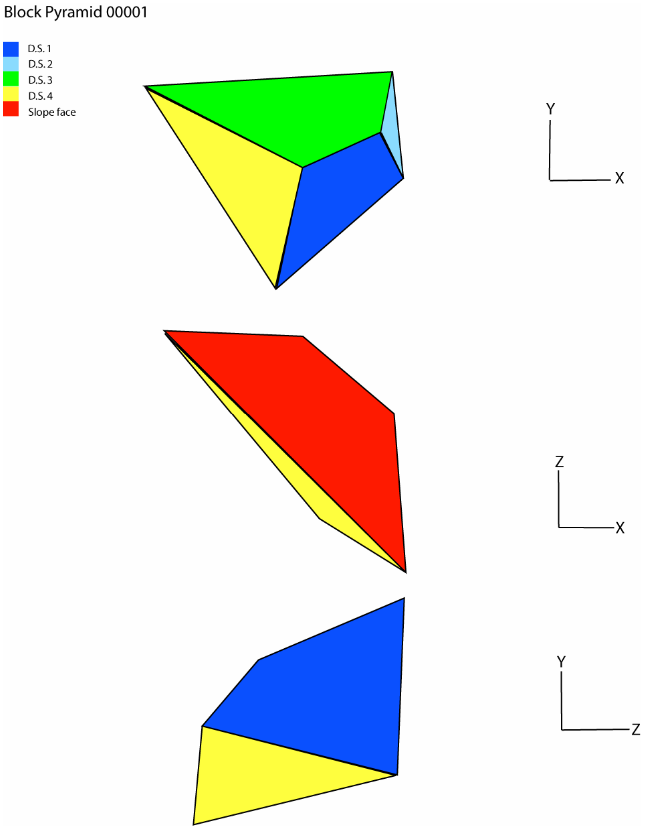

Figure 10: Three-dimensional block shapes obtained from the block theory analysis of the four discontinuity sets recognised in the headscarp of the Clanwilliam landslide.

5. MODELLING RESULTS

A preliminary 3D-distinct element model was constructed using an elastic material, the dominant 4 discontinuity sets, and friction angles of 30, 20, and 10^{o} along the discontinuity surfaces. However initial simulations did not indicate slope instability. A second series of models were built using the same discontinuity orientations but varying the discontinuity spacing and adding variability (standard deviation of 5^{o}) to the dip and dip direction. This second series of models also implied a stable slope configuration. A third series of models investigated the addition of the fifth discontinuity set mentioned in section 4 which was originally thought to be of minor importance. This third series of model indicated a slope failure when the friction angle along the discontinuity surfaces was reduced to 10^{o}. A friction angle of 10^{o} along the discontinuity can be considered to be very low value. Hungr and Evans (2004) noted that this landslide occurred during snowmelt and the increase pore water pressure could have contributed to reduce the effective friction angle to such low values. In the first and second models the spacing of the various discontinuities was kept constant at 5 m. In a third model the spacing of the sets was varied between 1 and 10 m based on field observations. The third model also led to slope failure when the friction angle along the discontinuities was 10° (Fig. 11). The resulting failing blocks have dimensions similar to those observed in the field.

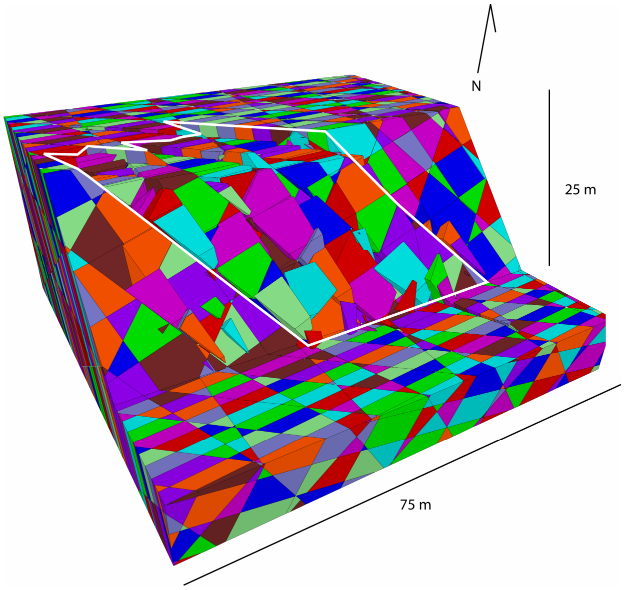

Figure 11: Slope failure in a 3DEC model of the Clanwilliam Landslide with variable discontinuity spacing and 5 discontinuity sets. Main failure outlined in white.

6. DISCUSSION

6.1 Potential failure mechanisms

The kinematic analysis and the deterministic wedge analysis using the average orientation of the four discontinuity sets identified in the stereonet suggested stable slope conditions. The combination analysis in Swedge using all discontinuities recorded at the headscarp of the Clanwilliam Landslide suggested that 20 wedges could be formed with a factor of safety below one. This highlighted the importance of the discontinuities not assigned to a set and to not solely rely on mean joint orientations. This could be because of the limited data set used in this analysis or the importance of random joints. The role of random joints is difficult to assess in conventional stability analysis but attempts have been made to assess this using discrete fracture networks (Grenon and Hadjigeorgiou, 2003).

The importance of considering all the discontinuity measurements was reinforced when only stable slope geometries were obtained in the 3D distinct element code even after introducing variability in the orientation of D.S. 1, 2, 3, 4. 3DEC models with discontinuity sets 1, 2, 3, and 5 led to slope failure further emphasizing the importance of the minor discontinuity set. Similarly, the block theory analysis using D.S. 1, 2, 3, 4 resulted in a finite and removable block but with a factor of safety of ~4 for a friction angle of 30° on the discontinuity surfaces and ~1.2 for a friction angle of 10° on the discontinuity surfaces. When the block theory analysis is performed with D.S. 1, 2, 3, 5 the factor of safety is ~1.0 for a friction angle of 15° on the discontinuity surfaces.

Rock slope failures are usually progressive processes where small movement accumulates along discontinuity and rock bridges are broken over a period of many years until a critical state is reached. Back-analysis such as the one presented in this paper highlights that calculated friction angles (10-15° in this case) are only the value needed to reach equilibrium and might not represent physical strength of the rock mass or along the discontinuities.

Another assumption used implicitly in all the analyses presented in this paper is the constant slope orientation. This is a simplification of the natural terrain since as noted by C. Bunce (personal communication, 2007) the pre-failure topography of the study area was a promontory in the landscape, which could allow more kinematic freedom than suggested by the analyses assuming a single constant slope orientation.

6.2 Potential trigger

The importance of a potential seismic trigger was assessed by consulting the Earthquake Database of Natural Resources Canada (2007). According to the earthquake database there were no seismic events recorded within a 100km radius of Revelstoke for the period between March 1st and April 2nd 1999. The weather conditions prior to the failure were presented in Figure 3. The only significant amount of precipitation (20-25mm/24hr) was recorded 11 days before the slope failure. The maximum and minimum air temperatures during that precipitation event were above zero at the lake level. The day before and the day of the failure had relatively high (for that period of the year and region) maximum temperature and minimum temperature below zero. These freezing and thawing cycles could have influenced the pore water pressure by obstructing some of the discontinuities with ice near the surface. This phenomena has been described or suggested at a range of slope failure scales (Bjerrum and Jorstad, 1968; Gardner, 1983; Haeberli *et al.*, 1997. EBA Engineering Consultants Ltd., 2004). It is suggested that this mechanism could potentially explain the low friction angle indicated in the 3DEC models for slope failure.

7. CONCLUSIONS

Using combination surface wedge analysis, block theory and 3-dimensional distinct element analysis simple and complex wedge blocks appear to be a feasible failure mechanism for the Clanwilliam Landslide. The surface wedge analysis method took into account all the discontinuity measured at the site but did not consider the block finiteness or discontinuity spacing. The block theory and 3DEC modelling used average discontinuity orientation for each sets but did consider the block finiteness and discontinuity spacing.

This paper demonstrated that the use of various 3D analysis techniques (kinematic analysis, limit equilibrium of surface wedges, block theory and distinct element) were useful in evaluating the role of the different discontinuity sets observed at the Clanwilliam Landslide. It was also emphasised that discontinuities orientations not assigned to a joint set during the kinematic analysis can have a critical role on the stability of a rock slope. These preliminary results are proposed while recognising that pre-failure and discontinuity geometries represent an important source of uncertainty and challenge to the back-analysis.

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