Discontinuity characterization and numerical modelling of the Paekakariki Landslide, Kāpiti Coast, New Zealand

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ABSTRACT
Large scalloped features in the hillslope above an old quarry near Paekakariki are inferred to be landslides scars triggered by the 1855 Wairarapa earthquake. The geology at the study area consists of Triassic to Jurassic greywacke rocks. Discontinuity orientations were acquired in the lower part of the slope using traditional compass method and using terrestrial photogrammetry for the upper reaches of the slope. The kinematic analyses of both datasets revealed that wedge sliding was the most feasible failure mechanism. The 3D distinct element models also led to a wedge type failure using the discontinuity set orientation based on the photogrammetry and an asymmetric sliding wedge using the discontinuity sets based on the field measurements.

RÉSUMÉ
Les grandes zones de gradin sur la pente au-dessus d'une ancienne carrière près de Paekakariki sont interprétées d'être des escarpements de glissements de terrain provoqués par le tremblement de terre Wairarapa de 1855. La géologie de la zone d'étude se compose de roches grauwacke d'âge Trias à Jurassique. L'orientation des discontinuités a été acquise à l'aide de la méthode traditionnelle de boussole dans la partie inférieure de la pente et à l'aide de la photogrammétrie terrestre pour la partie supérieure de la pente. L'analyse cinématique des deux ensembles de données a révélé qu'un dièdre était le mécanisme de rupture plus probable. Les modèles 3D d'élément distinct a également conduit à une rupture de type dièdre en utilisant que les orientations des discontinuités basée sur la photogrammétrie et un dièdre asymétrique en utilisant les orientations des discontinuités issues des mesures de terrain.

1 INTRODUCTION

The study area is located near the village of Paekakariki along the Kāpiti Coast approximately 35 km north-northeast from the capital of New Zealand, Wellington (Figure 1). This area is considered to be prone to slope failures due to the very steep and high slopes and headscarp features visible along this section of the Kāpiti Coast (Hancox and Perrin, 2006). The study area was chosen to help characterize the potential rock slope stability hazard to State Highway 1, the railway station at Paekakariki and the commuter railway itself. This area has also received renewed interest recently in the context of routing the proposed Transmission Gully transportation corridor (Opus, 2009 and 2011). Hancox and Perrin (2006) have suggested that the large landslide features in the hillslope above an old quarry near the Paekakariki train station were triggered by the 1855 Wairarapa earthquake (Figure 2). The Wairarapa earthquake caused major damage to the infrastructure in the Wellington and Wairarapa area and seismically induced landslides were also reported in the road cuts and natural slopes along the Hutt Valley and the Kāpiti Coast (Hancox, 2005). Evidence of the slope failures in the form of rockfall deposits at Paekakariki have been altered or removed by road construction in the 1930s (Hancox and Perrin, 2006).

1.1 Geology

The rock exposed along the slopes in the project area are Mesozoic (Triassic to Jurassic) aged sedimentary basement (greywacke) which form part of the Rakaia terrane, a tectonostratigraphic unit of the Torlesse (composite) terrane (Begg and Johnston, 2000).

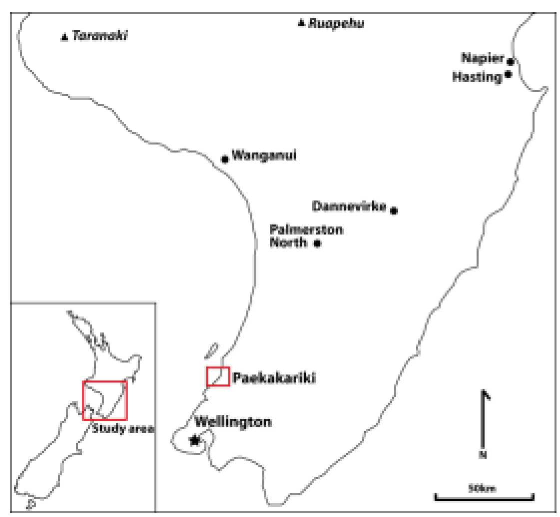

Figure 1: Location of the study area on the North Island of New Zealand.

Regionally these rocks are described as unfoliated to weakly foliated grey quartzo-feldspathic sandstone-mudstone sequences with thick, poorly bedded sandstone and minor conglomerate, mudstone, chert, basalt and very rare limestone (Begg and Johnston,

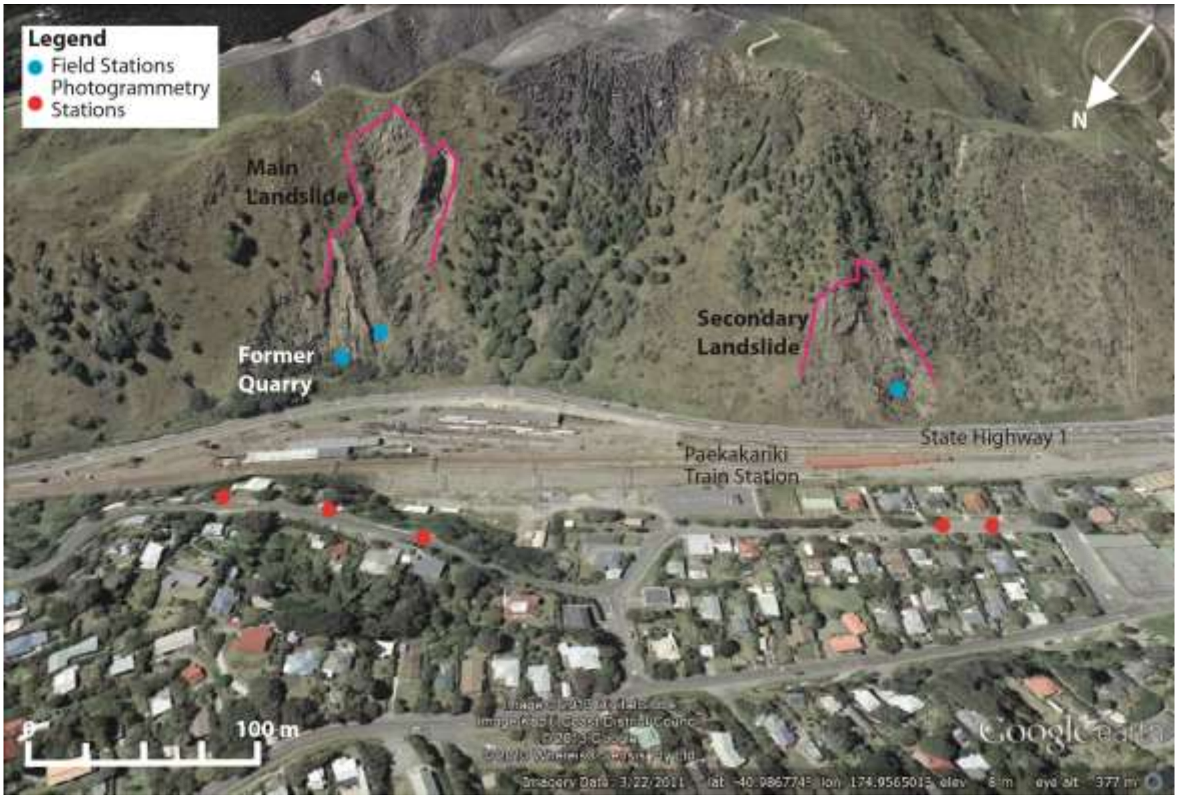

Figure 2: Overview of field and photogrammetry stations. March 2011 imagery from Google Earth.

2000). Recent work by van Dissen et al., (2013) suggest that large magnitude earthquakes (metre-scale displacement) can occur along the nearby Ohāriu Fault (1.5 km from the study site) with a 100-year conditional probability of rupture of approximately 4.9%. Figure 3 presents a map of the 224 seismic events with a magnitude greater than 4 within 25 km of Paekakariki included in the national New Zealand earthquake database for the period between 1840 and December 2012 (GeoNet, 2014).

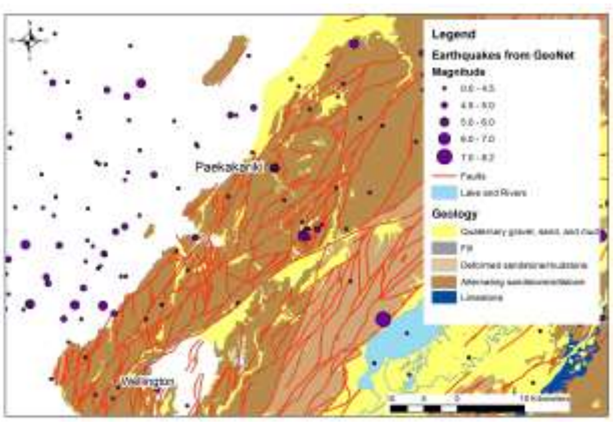

Figure 3: Simplified geology map and location of earthquakes with magnitude greater than 3.

2 SITE INVESTIGATION

The site investigation program for this project combined traditional field mapping and terrestrial photogrammetry. Three accessible outcrops along the base of the hillslope (Figure 2) were selected to describe the lithology, rock mass conditions, and measure discontinuity orientation and characteristics. These observations were used as input and constraints for the subsequent slope stability analyses. The recorded observations align with the guidelines set by the New Zealand Geotechnical Society (NZGS, 2005). The rock mass quality was estimated using the Geological Strength Index (GSI) as described in Marinos et al. (2005). The GSI takes into account the rock mass structure and the surface condition of the discontinuities present.

Terrestrial photogrammetry was used to obtain information about the discontinuity orientation in the upper reaches of the project area, which could not be physically accessed. Terrestrial photogrammetry is a technique which creates 3D models of rock outcrops by taking two digital photographs from different angles of the same target on the scarp of the landslide. The software Sirovision v 5 (CAE Mining, 2012) was used in this project to create and georeference (using camera coordinates and line of sight) the 3D models and to extract discontinuity orientation and persistence (Figure 4). Sirovision has previously been used to assess discontinuity orientation on road cuts (Hanenberg, 2008) and coal mines (Maconochie et al., 2010). Long range terrestrial photogrammetry has also been successfully used to characterize discontinuities in natural slopes by Sturzenegger and Stead (2009) and Brideau et al. (2012a). This remote sensing technique was particularly useful at this site as it allowed for discontinuity information to be safely collected from the steep upper reaches.

A summary of the discontinuity set orientation obtained by each site investigation technique is provided in Table 1. Figure 5 presents the stereonet of the combined datasets where five discontinuity sets were identified. The combination of the two data sets is considered to be complementary as they can compensate for the scale (field measurements) and orientation (photogrammetry) biases of each technique and they sample different parts of the study area. The average rock mass quality using the GSI was found to be between 40-60 (Figure 6) but it decreased to 20-30 near tectonic structures (shear zones). Field estimates of the unconfined compressive strength (UCS) for the greywacke units present at the site suggested that it was strong (50-100 MPa, as defined in NZGS, 2005).

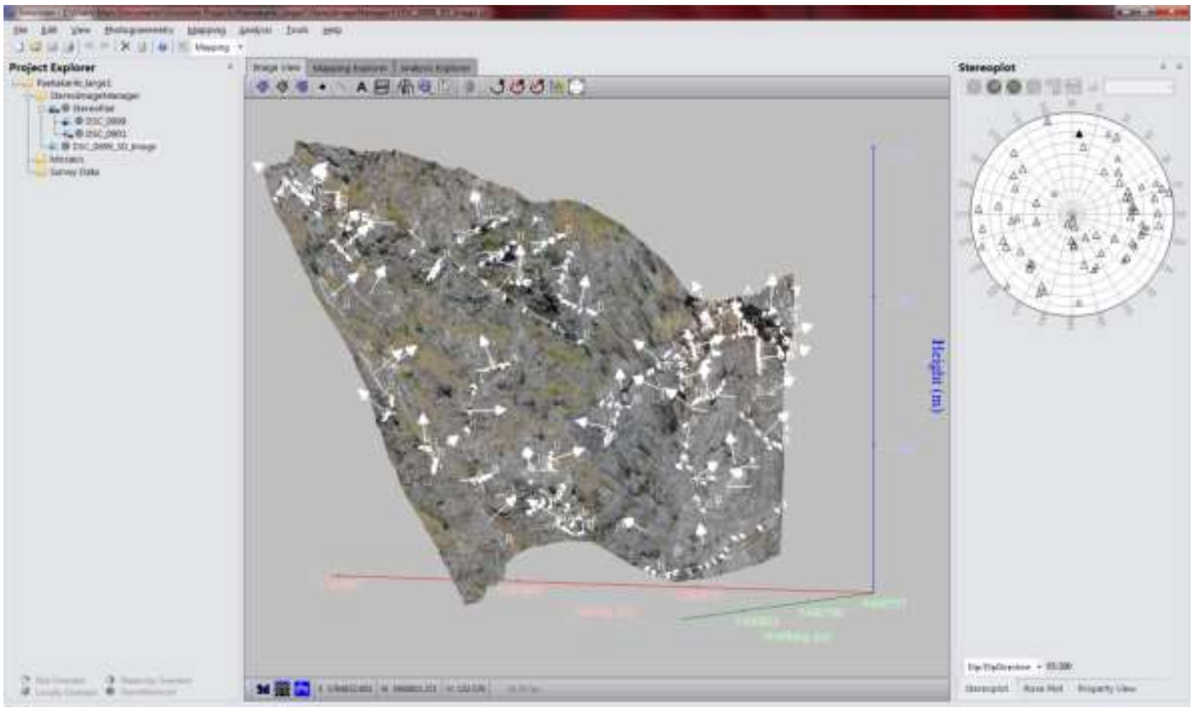

Figure 4: Example of discontinuities identified in the 3D terrestrial photogrammetry model

Point load tests on samples collected at the field station investigated were used to further refine the intact rock strength estimate. Samples were cut into regular-shaped blocks and tested according to the guidelines from ASTM (2010). Only six of the thirteen samples collected in the field provided valid test results. A valid result was obtained when the material failed through intact rock material and didn't follow a pre-existing discontinuity surface. This suggests that the pervasive fracturing/fabric present at the site due to the shear zones strongly influences the rock mass strength. The average I_{s50} obtained for the valid results was of 3.13 MPa which assuming a correlation factor of 23 between the I_{s50} and UCS (ASTM, 2010) corresponds to an average UCS of 72 MPa.

Table 1: Summary of discontinuity set orientations

Dataset	Discontinuity set	Dip (°)	Dip direction (°)
Terrestrial Photogrammetry	DS1	57	256
	DS2	39	336
	DS3	64	063
Traditional field measurements	DS2	45	319
	DS3	81	052
	DS4	89	136
	DS5	24	152
Combined datasets	DS1	53	257
	DS2	41	331
	DS3	66	061
	DS4	87	143
	DS5	30	153

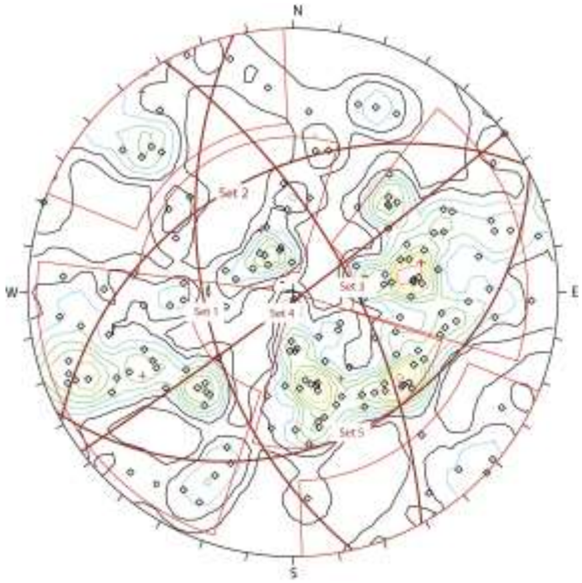

Figure 5: Stereonet of the discontinuity sets identified when combining the field and photogrammetry data sets

3 Slope Stability Analyses

3.1 Kinematic Analysis

Dips (Rocscience, 2012) allows the user to analyse and visualize structural data using stereographic projections. The combined structural data from the field measurements and terrestrial photogrammetry was used to conduct a kinematic analysis to identify feasible failure mechanisms. This analysis tests for three simple structurally-controlled failure mechanisms: toppling, planar sliding and wedge failure (Wyllie & Mah, 2004). The pre-failure hillslope orientation was estimated using ArcGIS (Esri, 2010) to be approximately 50°/305° (dip/dip direction). The friction angle along the discontinuity surfaces was assumed to be 35° as most discontinuity were found to be planar and rough (Goodman, 1980). The kinematic analysis (Figure 7) suggests that wedge sliding is the most likely failure mechanism with planar sliding and toppling being only marginally feasible. This is consistent with the wedge shape morphology of the failure scar (Figure 2).

3.2 Three-dimensional distinct element

3DEC is a three-dimensional distinct element software by Itasca (2008). The rock mass is represented by a collection of blocks bounded by discontinuities. As the intact rock strength of the greywacke was strong (~70MPa), the blocks were assumed to be rigid (i.e. they do not deform and all displacement is controlled by the discontinuity orientations and strengths). Two models were investigated to assess the influence of the discontinuity set orientations. The first model used the sets identified in the field investigation while the second model used the data from the terrestrial photogrammetry (Figure 8). It is observed that both models lead to a similar deformation pattern. The model applying the discontinuity sets based on field measurements has an asymmetric (slope parallel rotation) component similar to that observed by others in the field (Yan, 2008) and numerical models (Brideau and Stead, 2012).

Figure 6: Geological Strength Index (GSI) estimates (modified from Marinos et al., 2005). Photographs are of outcrops at the main landslide field station. See Figure 2 for location.

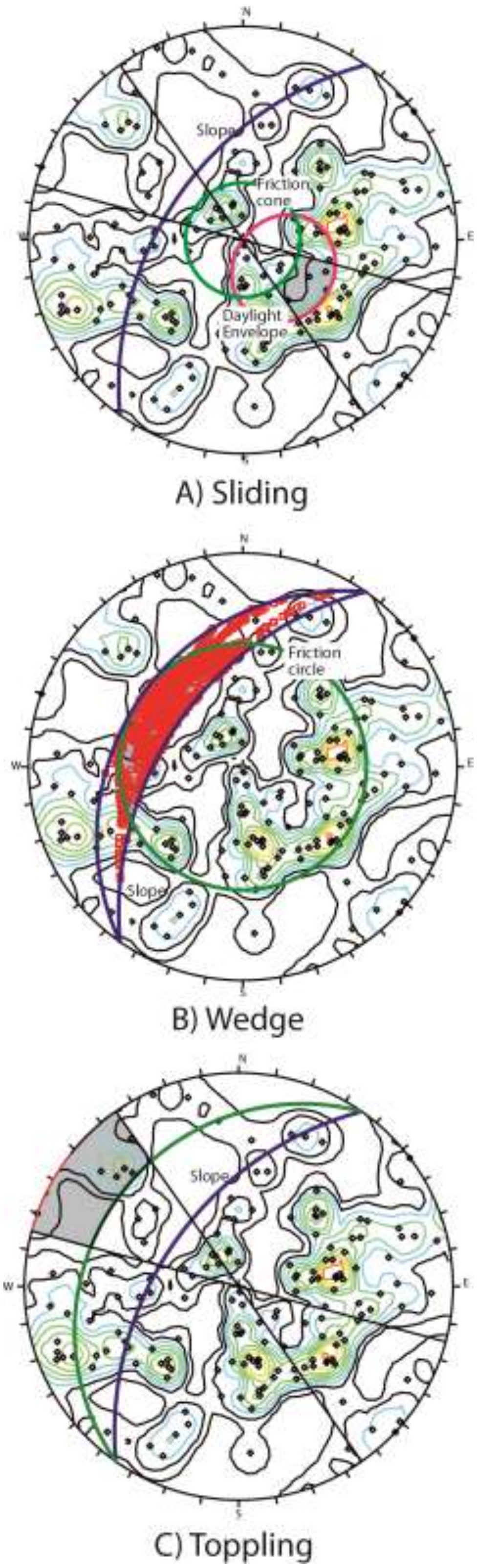

Figure 7: Kinematic analysis using the combined discontinuity dataset. The analysis assumed a slope orientation 50°/305° (dip/dip direction) of and a friction angle of 35°.

4 DISCUSSION

The difference between the discontinuity sets orientation identified in the traditional field measurements and terrestrial photogrammetry surveys are attributed to the orientation and scale biases, resolution, and occlusion of the two techniques. Similar observations and conclusions have been discussed in Sturzenegger and Stead 2009. Another possibility is that the upper part of the slope (where measurements from the terrestrial photogrammetry was collected) represents a distinct structural domain that differs to the lower portion of the slope (where the field measurements were collected). A similar situation was encountered by Brideau et al. (2012b).

The results of the kinematic and 3D distinct element analyses suggest that even in its static state the rock mass at Paekakariki is pre-disposed to slope instability and currently stable due to the effective strength along the discontinuities. Based on the latest seismic hazard model, the study area is located in a region that could potentially experience a PGA for a shallow soil in the order of 0.4 - 0.6g for a 475 year return period and 0.6 - 0.8g for a 2500 year return period (Stirling et al., 2012). The seismicity only need to reduce the effective friction angle along the discontinuities by dynamic loading (reducing the normal stress) and/or effective cohesion (fracturing the rock bridges between non-fully persistent discontinuities) to trigger a slope failure.

Currently the State Highway 1 follows the Kāpiti Coast and provide the main road access to the nation's capital, Wellington. The railroad line also follows this transportation corridor. The vulnerability of the coastal highway to earthquake triggered landslides is one of the factors that motivated to New Zealand government to propose the construction of Transmission Gully Highway as an alternative land access route. This is a 27 km new highway that not only avoid the unstable slopes discussed in this paper for there are also many other ones further south (Figure 9). While the recent Cook Strait (magnitude 6.5, July 21, 2013, located 100 km south east), Lake Grassmere (magnitude 6.6, August 16, 2013, located 110km south east) and Eketahuna earthquakes (magnitude 6.2, January 20, 2014 located 85 km to the north east) have not triggered widespread landslide activity (GeoNet, 2014), they have provided timely reminder that the study area is affected by both earthquake and landslide hazards.

5 CONCLUSIONS

The slope near Paekakariki along the Kāpiti Coast were investigated using a combination of traditional field survey and terrestrial photogrammetry. Both techniques were found to be complementary as they have different scale (field measurements) and orientation (photogrammetry) biases and they sample different parts of the study area. Five discontinuities sets were identified at the site. The rock mass quality has a GSI value of 40-60 away from discrete shear zones and 20-30 within these structures. The Uniaxial Compressive Strength of the sandstone at the site was estimated to be approximately 70 MPa. Kinematic and three-dimensional distinct element models found that asymmetric wedge sliding was the likely failure mechanism of the landslides that occurred near Paekakariki.

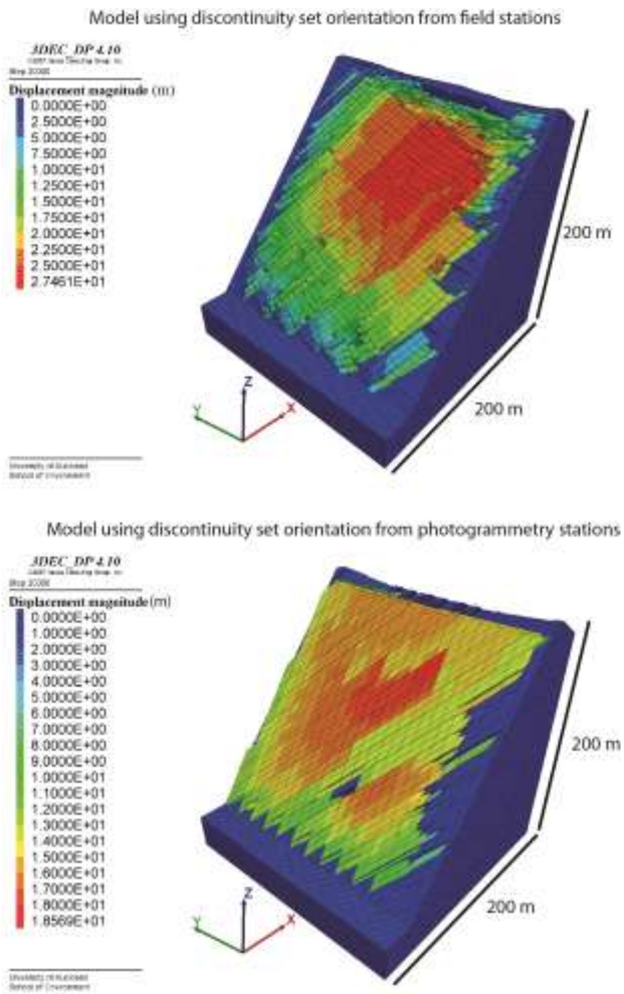

Figure 8: Total calculated displacement obtained in the three-dimensional distinct element models using discontinuity set orientations from the field measurements and photogrammetry analysis

Figure 9: Unstable slope 2.5 km south of the main study area

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