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An Engineering Geological Analysis of the Tutira Landslide Dam, Hawke's Bay, New Zealand.

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ABSTRACT

The Tutira landslide dam is located in northern central Hawke's Bay, and has resulted in the formation of three lakes: Tutira; Waikapiro; and Orakai. The landslide occurred approximately 7200 years ago, as determined by carbon dating of lake-core sediments. The slope failure occurred in a Plio-Pleistocene sedimentary sequence of interbedded limestones, mudstones, and sandstones. Traditional field mapping (including the use of the Geological Strength Index) and terrestrial photogrammetry were used to characterize the lithology, rock mass conditions and discontinuities present in the headscarp. There was good correlation between the compass and photogrammetric discontinuity measurements, revealing three distinct discontinuity sets. The bedding dips at a shallow angle into the slope, and intersects with two vertical and orthogonal joint sets, forming large sized blocks in the headscarp. Kinematic analysis was undertaken, and showed that the landslide could not have failed by simple sliding, wedge, or toppling failure. The structural and geological data along with lab strength data were used as input for 2D limit equilibrium models. These were designed to analyse the triggers and mechanisms of movement of the Tutira landslide. The Hawke's Bay is a region which experiences both intense precipitation storms, and frequent seismic activity, therefore high pore pressure and seismic loading, as well as fluvial incision are important parameters included in the models. The results of these models and a discussion about them are detailed in this paper.

Keywords: landslide dam; terrestrial photogrammetry; limit equilibrium

1 INTRODUCTION

The Tutira landslide dam is a large rare event situated in northern central Hawke's Bay, New Zealand (Figure 1). It dammed the ancient Papakiri Stream to form three lakes: Tutira; Waikapiro; and Orakai (Lowe, 1987). Significant research has been undertaken on lake core sediments from Lake's Tutira and Waikapiro (Page et al., 2010 and references therein), and radiocarbon dating of wood found at the base of the lacustrine sediments has indicated a minimum formation age of 7200 years BP for the lakes and landslide. Due to the large size of the Tutira landslide dam (200Mm³) it is an important analogue for modern and potential large landslides. These large landslides can have catastrophic impacts, including disrupting and damming fluvial systems, as the Tutira landslide has done. This adds an extra dimension of hazard, as the dam deposits have the potential to cause significant upstream flooding, and/or breach leading to downstream flash flooding (Costa and Schuster, 1988). The aim of this study was to characterize and analyse the triggers and mechanisms of failure for the Tutira landslide dam. This was done using a integrated approach of field investigation, terrestrial photogrammetry, laboratory analysis, and limit equilibrium modelling.

2 LOCAL GEOLOGY

The geology of the Hawke's Bay area is influenced and controlled by the subduction of the Pacific Plate beneath the Australian Plate. The landslide failed in an alternating sequence of Plio-Pleistocene limestones, mudstones and sandstones, known as the Petane limestone group. This group is situated within in the 450km² Tangoio block, an uplifted plateau of the central Hawke's Bay (Haywick et al., 1991). Three formations outcrop on the Tutira headscarp: the Kaiwaka limestone; Devil's Elbow mudstone; and Waipatiki limestone (in order from the top to bottom of the scarp). Below these units and obscured by the deposit are the Te Ngaru mudstone, Tangoio limestone and Mairau mudstone units. These units are undeformed with little post depositional structural disturbance, in contrast to other regions of the East Coast Deformed Belt (Kamp, 1982). The region experiences frequent seismic activity, with several active faults within a 30km vicinity of the Tutira landslide – the closest being the Rangiora fault (GNS, 2011).

3 DISCONTINUITY ANALYSIS

Information on the discontinuities present at the Tutira landslide headscarp was derived from traditional compass/clinometer measurements and terrestrial photogrammetry. Terrestrial photogrammetry is a technique which creates 3D photographic models of rock outcrops, allowing for discontinuity measurements to be obtained from them. The models are constructed from two photos of the headscarp taken at different angles. The camera positions and target on the headscarp were determined using RTK GPS to allow accurate georeferencing of 3D image models and orientation information to be measured from them. This is an efficient and rapid method which allows measurements to be taken from inaccessible and hazardous outcrop areas. It is complimentary to compass measurements as the two techniques capture different persistence discontinuities, with the compass data recording the small scale features, aperture, infilling and roughness while terrestrial photogrammetry captures high to medium persistency discontinuities. At Tutira the two data sets showed good correlation, and revealed three distinct discontinuity sets (Figure 2). The first one is a gently dipping bedding set, which dips to the south-east into the slope. This bedding set intersects with two orthogonal steep joint sets to form large sized blocks in the headscarp. Kinematic analysis was undertaken, and revealed that toppling, sliding or wedge failure were not the main mechanisms of slope instability. The pre-failure slope was assumed to be 30° based on surrounding hillslopes, and the assumed friction angle was 30° due to the dominant limestone lithology, as well as the roughness and interlocking of the discontinuities. At the current slope angle of 42° a small concentration of poles fall within the toppling region – which is confirmed by evidence of block falls on the talus slope. It can be concluded that structural features are not the main reason for instability

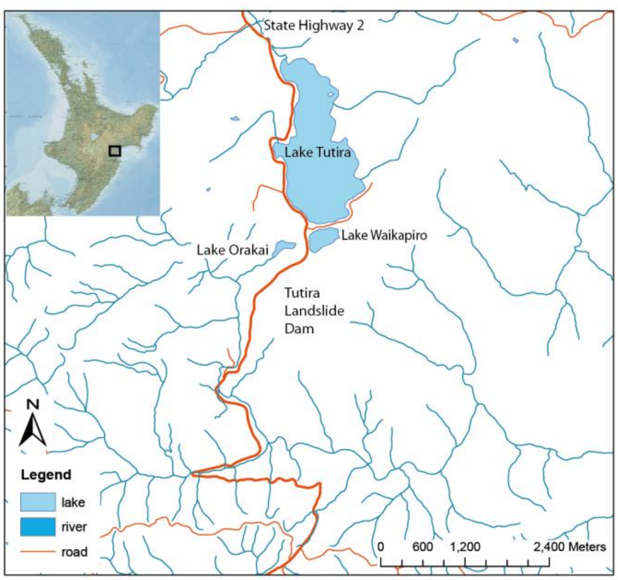

Figure 1: Location of the Tutira landslide dam.

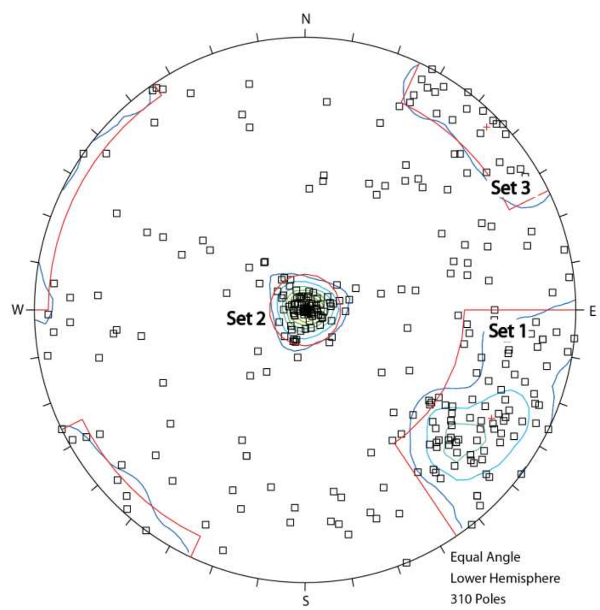

Figure 2: Stereonet of discontinuity orientation found at the Tutira headscarp based on field and photogrammetric measurements. The red boxes delineate the three discontinuity sets.

4 ROCK MASS PROPERTIES

The NZGS (2005) nomenclature defines the different rock units as follows:

- slightly weathered, yellow-brown, bedded, limestone, strong, steep orthogonal joint sets and bedding dipping 0 -10° into slope (Kaiwaka Formation).
- slightly weathered, blue-grey, homogenous, mudstone, very weak, closely spaced joints (Devil's Elbow Formation).
- moderately weathered, yellow-brown, bedded, limestone, weak, shallow dipping bedding intersecting steep orthogonal joints (Waipatiki Formation).

There is a wide range in Geological Strength Index (GSI) values for the Tutira headscarp (Figure 3). The Devil's Elbow mudstone has the highest rock mass quality with a range of 55-65, next is the Kaiwaka limestone with 45-55, and the Waipatiki limestone has the lowest quality with a range of 35-45. Schmidt hammer rebound values were recorded from Kaiwaka limestone outcrops, and converted to unconfined compressive strength (UCS) using O'Rourke's (1989) equation for limestone formations to provide an UCS estimate of 80MPa, consistent with field estimates. The cone indenter was used in the laboratory to provide an UCS of 4MPa for the Devil's Elbow mudstone unit. The weak nature of the Waipatiki limestone made it unsuitable for laboratory testing and Schmidt hammer readings, and an UCS of 10MPa was estimated from rock hammer strength estimates. The rock mass conditions of the Tutira headscarp therefore show a large variation, with hard strong limestone underlain by weak mudstone and limestone.

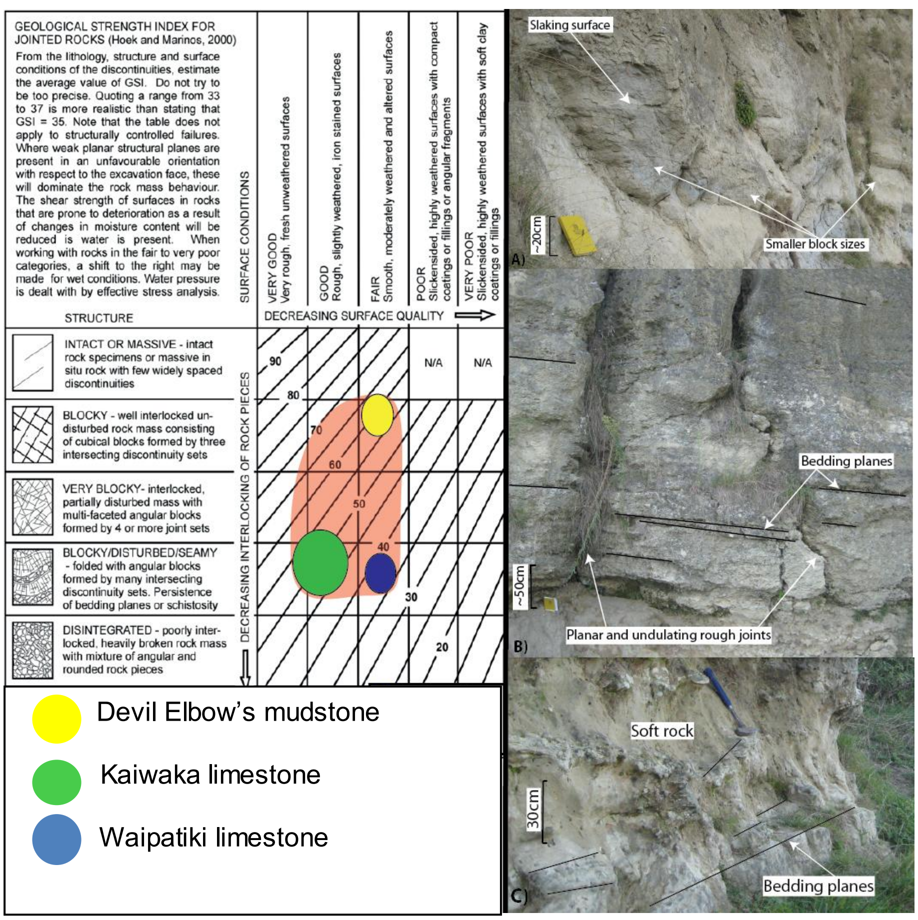

Figure 3: A GSI chart displaying rock mass quality for the different units, with the red circle displaying the overall range of values for the headscarp. Photo A) the Devil's Elbow mudstone; B) the Kaiwaka limestone; C) the Waipatiki limestone.

5 LIMIT EQUILIBRIUM MODELLING

Limit equilibrium method of slices modelling was undertaken to analyse the triggers for the Tutira landslide and the controls of rock mass strength on stability. The slip surface was defined as circular, the Hoek-Brown failure criterion was used to define the materials, and the Morgernstern and Price method was used to calculate the Factor of Safety (FoS). Full strength and residual strength models of the prefailure rock mass (Table 1) were constructed in limit equilibrium software. The basic geometry of the models is a 160m high slope, at a 30° slope angle. The models contain simplified lithology composed of three layers; the Kaiwaka Limestone; Devil's Elbow Mudstone; and Waipatiki Limestone (Figure 4).

The initial FoS for the full strength model was 2.017, and 1.217 for the weak model. Three important triggers considered in the models are high pore water pressure, stream incision and seismic loading, as the Hawke's Bay experiences intense precipitation storms and frequent seismic activity. The pore pressure of the slope was defined as Ru – the pore pressure ratio, which is the relationship between the pore water pressure and weight of the rock mass. The mudstone was considered to be impermeable based on field investigations and consistent with the literature (Haywick, 2004). An increase in the Ru value to 0.3 (water pressure is not expected to exceed 0.3) does not cause failure in the strong model, while for the weak model failure occurs at Ru 0.3 (Figure 5). A combination of a 20m deep river incision channel and an Ru value of 0.3 does not result in failure for the strong model, with the weak model having a FoS of 1.1 for a 20m deep channel with no pore water pressure. The 1931 M7.8 Napier Earthquake was used as an analogue for seismic loading conditions the Tutira area could recieve. In this earthquake the Tutira region experienced MM9 intensity shaking – with an estimate of mean peak horizontal ground acceleration of 0.3 – 0.5g (Hancox et al., 1997). It is standard practise to use 2/3 of this value due to the effects of attenuation and directivity, therefore 0.2g and 0.34g were used to capture the impact of a large magnitude earthquake. At 0.2g seismic loading failure does not occur, even with a Ru value of 0.3, although the model is marginally stable. However if the intensity is increased to 0.34g failure occurs at an Ru value of 0.2. At a seismic load of 0.5g, which could represent topographic amplification, failure occurs for all rock mass strength considerations.

Table 1: Overview of rock mass properties for the limit equilibrium models.

	Kaiwaka Limestone		Devil's Elbow Mudstone		Waipatiki Limestone	
	Strong	**Weak**	**Strong**	**Weak**	**Strong**	**Weak**
GSI	52	40	50	40	37	35
UCS	80MPa	20MPa	4MPa	2.3MPa	10MPa	5MPa
Mi	10	5	7	5	7	5

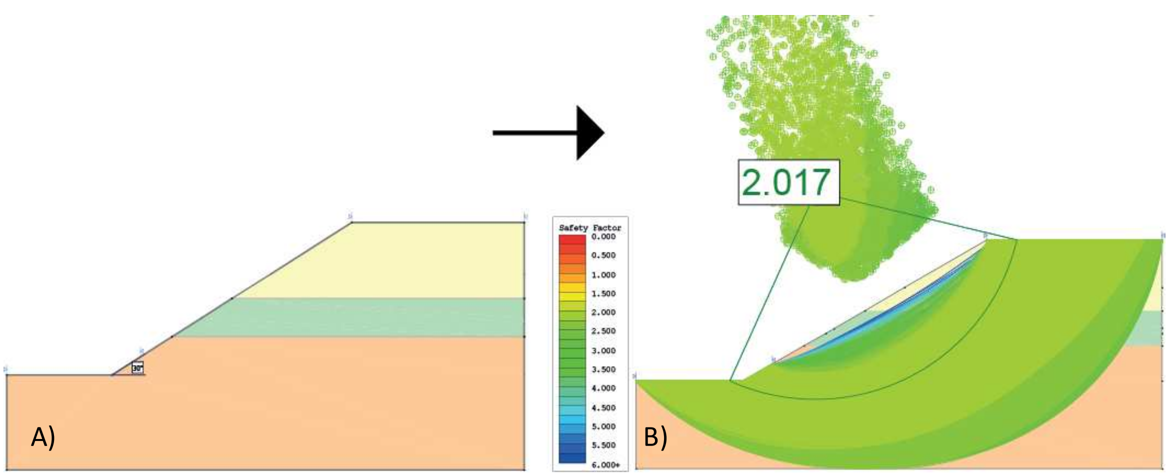

Figure 4: A) Model of the Tutira landslide headscarp with the three lithology layers displayed. B) The critical slip surface and FoS for the strong model without any pore water pressure or seismic loading.

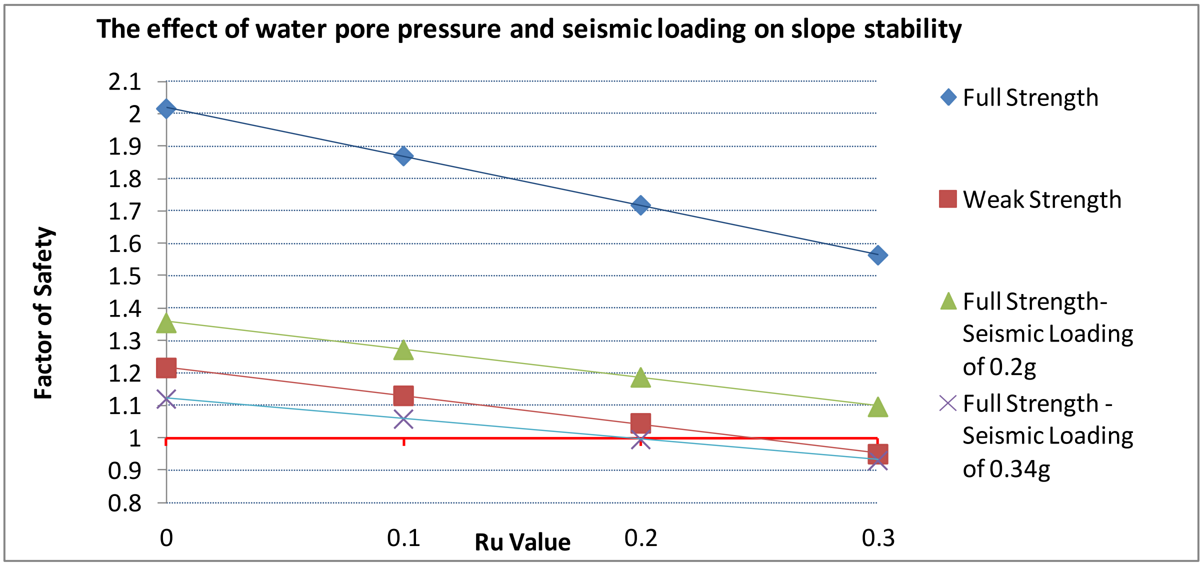

Figure 5: Graph displaying the effect of increasing pore water pressure in conjunction with the intensity of seismic loading on the FoS and stability of the Tutira hillslope

6 DISCUSSION

The main factors controlling the stability of the Tutira hillslope are rock mass properties rather than structural features. Kinematic analysis revealed that the hillslope could not have failed by toppling, planar sliding, or wedge failure – due to the fact the bedding dips into the slope, as well as the roughness and interlocking of the joints. It is therefore more plausible that the highly variable rock mass conditions present at the Tutira hillslope are the major control on instability. Even though there are a wide range of rock mass conditions - the rock mass can be generally considered weak, with a seamy structure due to persistent bedding, and good to fair surface conditions. The weaker layers are at the bottom of the slope, and therefore have a greater control on stability. In particular silt laminations and rip-up clasts were observed in the Waipatiki formation, and cone indenter testing determined a UCS of 3.2MPa for these silt formations. These silt layers have also been observed in the stratigraphically lower Tangoio formation. This adds to the weakness of the layers. It may be that the basal failure surface is located within these weak layers beneath the Waipatiki formation, or along a contact between the permeable limestone and impermeable mudstone. The basal failure surface was unable to be identified due to debris covered slope of the scarp. The potential triggers for the Tutira landslide dam could be excessive pore pressure, stream incision and seismic loading. The modelling has shown that for the full strength model increases in water pressure, stream incision and combinations of the two – do not result in slope failure. However slope instability was induced by a seismic loading of 0.34g combined with high pore water pressure. If the seismic loading is increased to 0.5g, failure occurs instantaneously. It may be that the source of seismic energy may have been close to the Tutira lake landslide, but if it was further away wet ground conditions would have had to been a precursor for failure. However it is important to assume the worst baseline conditions before labelling a landslide seismically induced (Jibson, 1996). The weak strength models were barely stable to begin with, and failed with increasing pore pressure. To understand which model was the more plausible the volumes of the different interpretations were calculated to assess the closest fit to reality. The full strength model had a larger volume then the weak; however both were an order of magnitude lower than reality. Additional support for the full strength model is given by the fact the hillslopes of and around Lake Tutira remained stable during the 1931 earthquake. Potential seismic sources include the Rangiora, Patoka or Mohaka faults – which are within a 30km radius of Tutira. All these faults are listed as being active in the Holocene, and can produce earthquake of M6.4 and greater (Stirling et al., 1998). There have been numerous earthquake events recorded in the Hawke's Bay landscape, but there is no other record for one at 7200 years BP (Berryman et al., 2011: and references therein).

7 CONCLUSION

This investigation and study has shown that the most probable trigger for the Tutira landslide dam is a large magnitude earthquake which occurred approximately 7200 years ago. The full strength model was considered to be the more appropriate, as this region has experienced several large scale storms, and earthquakes which have not resulted in large scale failures in the Tutira area. It is possible that stream incision and weathering may have weakened or preconditioned the Tutira hillslope for failure. Kinematic analysis of the combined discontinuity data displayed that simple toppling, planar sliding or wedge failure were not the main mechanisms of failure. The close match between the 3D photo model data and compass measurements of the discontinuities illustrates the usefulness and reliability of terrestrial photogrammetry as a tool for remote sensing data collection. The underlying cause of instability is due to rock mass conditions, rather than the structural features of the headscarp. It could be that the basal failure surface is located along a contact between the limestone and mudstone – due to the permeability contrast, or within the weak limestone layers as a consequence of the silt laminations.

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