Controls on slope failures at the Te Toto Amphitheatre, New Zealand

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Abstract
The Te Toto Amphitheatre, on the north western slope of Mount Karioi, Raglan, New Zealand presents the geomorphic expression of a large (estimated 25-30Mm^3) ancient slope failure. The amphitheatre has a low angle floor, with near vertical back and side walls. Modern rockfall processes are observed as scree slopes near the side walls. Using discontinuity orientation measurements (N=301), a kinematic analysis suggests that toppling failure is a feasible failure mechanism for the rockfall.

The Geologic Strength Index (GSI) is used to estimate the rock mass quality of three geotechnical units identified during field mapping. These include a visually extensive Flow unit (GSI 60-65), scattered pockets of a Pyroclastics units up to 6m in thickness (GSI 40-45) and a 2m thick Volcanic sediment (GSI 40-45). Field estimates, Schmidt Hammer and point load tests suggested that the units have unconfined compressive strengths (UCS) of 60-200MPa (Flow), 20-40MPa (Pyroclastics) and 7-20MPa (Volcanic sediment).

Limit equilibrium modelling is performed to determine the mechanism and contributing factors for failure of the rock masses present. The Southern wall of the amphitheatre is used as a slope profile (average slope angle of 20°, steep coastal front of 50°). Model rock mass properties were determined using the Hoek-Brown failure criterion. A low angle anisotropy was introduced to represent the structural element of bedding. FOS < 1 values were achieved using lower bound material strength values and high porewater pressures (represented using R_u=0.4).

Keywords: Volcanic rocks, Slope stability, Limit equilibrium, Geologic Strength Index

1 INTRODUCTION
Failures in volcanic edifice have been linked to the strength of the geological materials, topography, seismic forces and fluid pressures (Voight and Elsworth 1997). The importance of rock mass strength was noted by Reid et al., (2001) who states that the depth and volume of a failed mass is dependent on the rock mass strength. The importance of testing the range of materials present at the edifice to gain a proper representation of rock mass strength was noted by Watters et al., (2000). Many studies in the literature are focused on failure of active volcanic edifices; this is generally because they are monitored for seismic acceleration, ground deformation, and magmatic activity i.e. Kilauea volcano, Hawaii (Okubo 2004), and the Canary Islands (Moss et al., 1999). However, slope failures in inactive/ancient volcanic materials have recently been recognised as potential slope hazards (Shea and Van Wyk de Vries 2010). The Te Toto Amphitheatre represents a slope failure in an ancient inactive edifice.

1.1 Study Area
The Te Toto Amphitheatre lies on the north-western slope of Mount Karioi near Raglan, New Zealand (Figure 1). This region of West Coast New Zealand is characterised by surf beaches, estuarine harbours, and scattered Pliocene - Quaternary aged monogenetic volcanic fields (Ngatutura, Alexandra, Okete, South Auckland) (Briggs and McDonough, 1990). The amphitheatre has a distinctive horseshoe shape, with steep sided walls and a hummocky, boulder filled central valley. This represents the geomorphic expression of an ancient slope failure, with the majority of material thought to be deposited offshore (Edbrooke, 2005). Similar features of a smaller scale are seen further along the coast line, with Woody Head and Spray Bay directly to the south (Figure 1). The Te Toto stream runs through the middle of the amphitheatre from the upper slopes of Karioi, draining out to sea at the coast. The amphitheatre runs for 1.2km north south, and 1km from the coast to the top of the amphitheatre. The geology consists of interbedded basaltic lava flows, coarse grained pyroclastics and volcanic sediments of the Alexandra group volcanics. Seismic records held in the GNS Science database suggest that there is low seismicity in the area.

Figure 1. Aerial photograph of the Te Toto Amphitheatre and map locating Raglan within the North Island of New Zealand.

2 METHODOLOGY

To analyse the factors which influenced failure at the Te Toto Amphitheatre, back analysis of the scarp was conducted using an integrated approach of field mapping, laboratory work and numerical modelling. Field work included detailed engineering geological mapping of the geologic units at the site, field descriptions including discontinuity measurements and intact strength estimates following NZGS Guidelines (2005) and the use of Schmidt hammer. Rock mass quality was estimated using the Geologic Strength Index. The Geologic Strength Index (GSI) is a system which quantifies field observations of rock masses into rock mass quality. It was developed by Hoek and Brown, (1997) and examines the structure and surface quality of the rock mass, including discontinuity sets, block geometry, weathering and roughness. A combination of Schmidt Hammer and Point Load tests were used to estimate UCS. A sensitivity analysis was performed using SLIDE 6.0 (Rocscience 2002) to determine what factors affected the stability of the slope.

3 RESULTS

3.1 Geotechnical units

Three geotechnical units were identified in the field, the Flow, Pyroclastics, and Volcanic sediment units. The most aerially extensive unit was the Flow unit, consisting of unweathered to slightly weathered basaltic lava flows. The Pyroclastics unit consisted of a clast supported volcanic breccia, this had an irregular erosive and intrusive contact with the Flow unit, reaching a maximum of 6 metres in thickness. The Volcanic sediment unit is observed as a continuous unit, up to 2 metres thick of fine grained sediment. It has a low angle dip of 10-15° and contacts below the Flow and Pyroclastics units. These are displayed on Figure 2, with their respective GSI estimates. The contacts between the Flow unit and the volcanic sediment and Pyroclastics irregular and undulating and are positioned roughly 10m above the valley floor. Point load test values (Figure 3) suggest that Flow had the highest material strength while Volcanic sediment the lowest. The Pyroclastics unit displayed an over estimated strength from point load tests due to only the clasts being tested, Schmidt hammer was found to be appropriate for estimating the intact material strength for this unit. Seepage was observed at a number of sites, particularly at the contact between the Pyroclastics and Volcanic sediment (Figure 4).

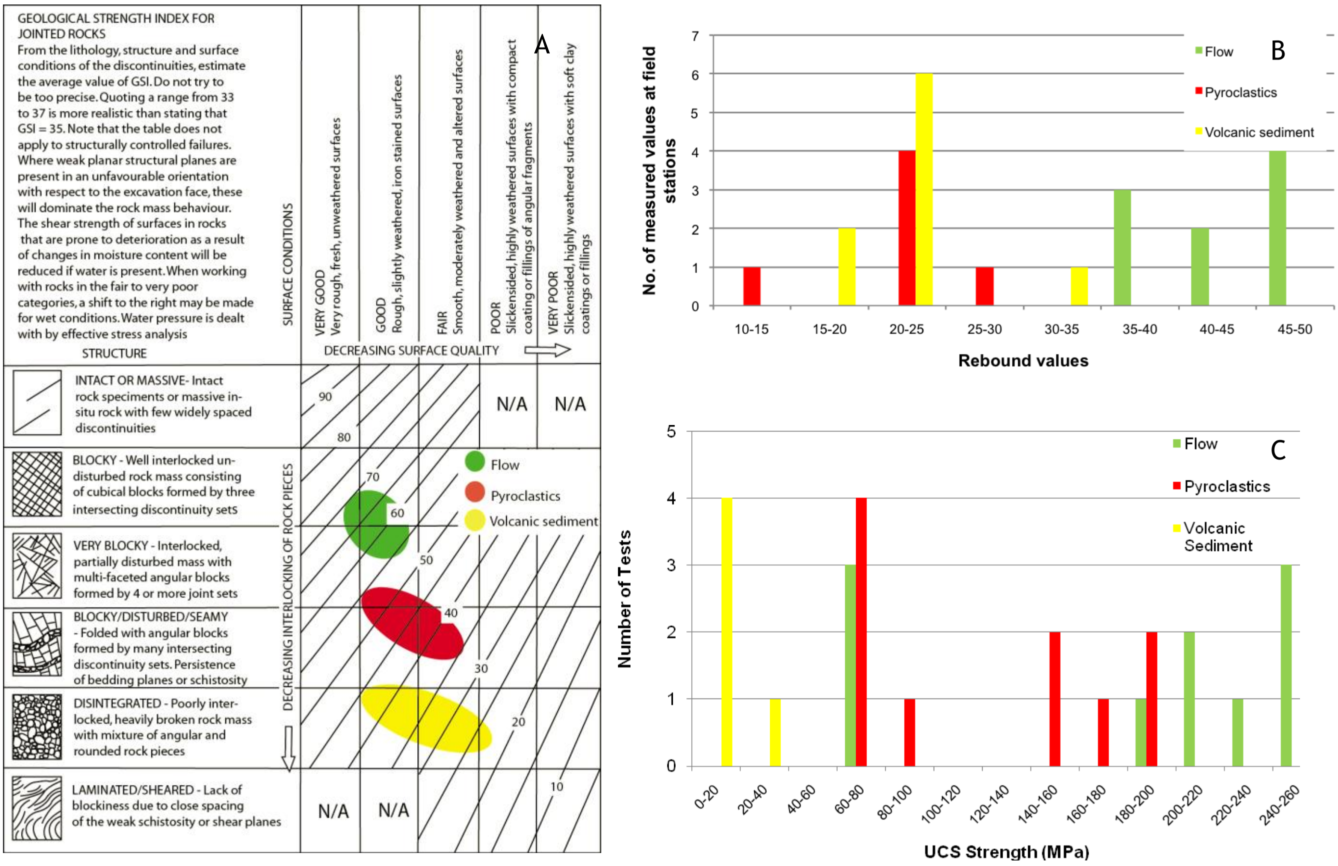


Figure 3. A) GSI table. B) Schmidt hammer rebound values. C) Point load test results.

Table 1. Discontinuity data for the 3 combined geotechnical units.

Discontinuity Set	Average Dip (°)	Dip Direction (°)	Primary Roughness	Secondary Roughness	Spacing (mm)	Persistence (mm)
I	03	357	Planar Undulating	Rough -Smooth	500-2000	2000-5000
II	80	138	Undulating	Rough	400-800	1500-3000
III	84	254	Undulating	Rough - Smooth	200-500	1000-3000
IV	76	032	Planar-Undulating	Rough	500-1000	800-3000

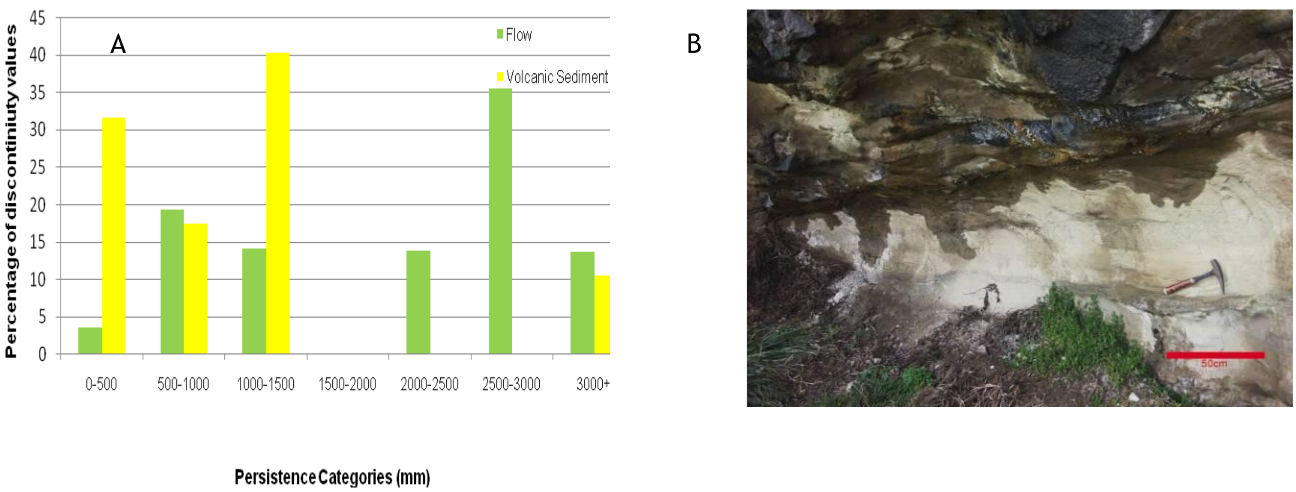


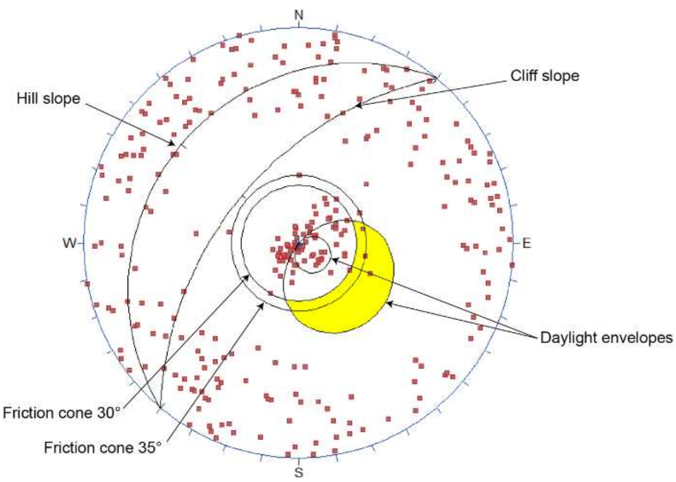
Figure 4. A) Histogram of Persistence, B) Seepage

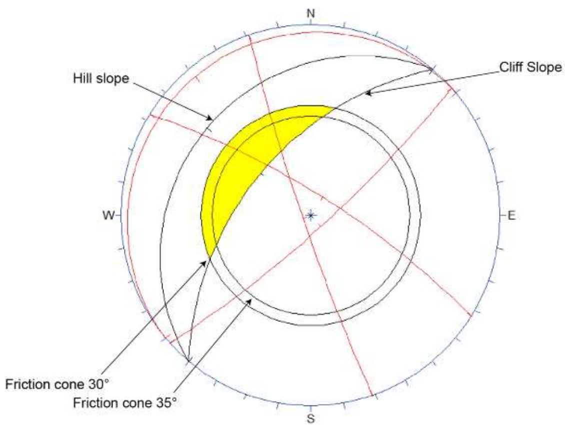
3.2 Kinematic Analysis

A kinematic analysis was performed considering toppling, planar sliding and wedge failure for two different regions of the Te Toto Amphitheatre. The analysis was performed using discontinuity data measured in the field (Table 1 and Figure 4), these are the combined discontinuities for all geotechnical units. Two structural regions were considered, the first representing a coastal cliff slope, the second an average hill slope. These slopes have a dip direction of 310°, the midpoint between the Northern and Southern wall orientations. Assumed effective friction angles between 30° – 35° are shown on each stereographic projection. These friction angles were estimated from roughness values from the discontinuity set most likely to influence the particular failure. Four main discontinuity sets were observed, three high angle and one low angle bedding influenced set.

Toppling analysis was performed for both the hill and the cliff slopes, but was found to only be kinematically feasible at the cliff slope. Figure 5 shows a stereographic projection for toppling failure at the cliff and hill slopes. A large portion (90%) of discontinuity set II lies within the toppling zone; these discontinuities are still in the toppling failure zone when the friction angle is changed ±5°. This suggests that toppling failure along discontinuity set II is kinematically feasible.

Planar sliding was not found to be kinematically feasible at either the cliff or hill slopes (Figure 5). One discontinuity is found in the cliff slope planar sliding zone; this is not enough to justify feasibility. There were also no observed field evidence for planar sliding. Wedge failure was not found to be kinematically feasible for the selected slopes (Figure 5).





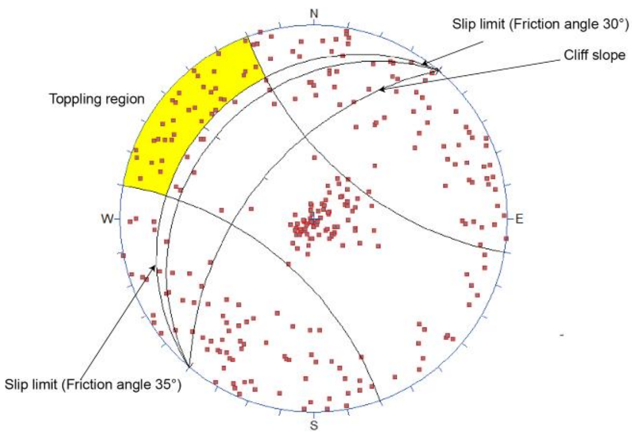


Figure 5 Kinematic analysis. A) Planar sliding. B) Wedge failure. C) Toppling.

3.3 Limit Equilibrium modelling

To assess the importance of the various contributing factors to the slope failure, a sensitivity analysis was performed on the Southern wall of the Te Toto Amphitheatre. This considered the effects of the material parameters, presence of water (using R_u coefficients). An anisotropy (cohesion less with a friction angle of 35°**)** was introduced to all three units as bedding (average dip of 10-15°) was a pervasive fabric throughout the amphitheatre. The material parameters used are shown in Table 2. To achieve FOS values of less than 1.0, lower bound material strengths were used, an R_u value of 0.4 and a low angle anisotropy. The minimum failure surface is shown in Figure 6. From the sensitivity analysis it was evident that groundwater has had the greatest effect on slope stability, followed by the anisotropy and weak materials. Mohr-Coulomb materials displayed higher FOS values than Hoek-Brown materials in all models.

Table 2 Rock mass parameters used in limit equilibrium modelling

Unit	**σ_{ci} (kPa)**	**GSI**	**mi**	**c (kPa)**	**phi (°)**	**m_b**	**s**	**a**
Flow	75000	57	22	1368	56.0	4.74	0.0084	0.504
Pyroclastics	24000	27	16	418	36.9	1.18	0.0003	0.527
Volcanic sediment	7000	37	10	270	27.2	1.05	0.0009	0.514

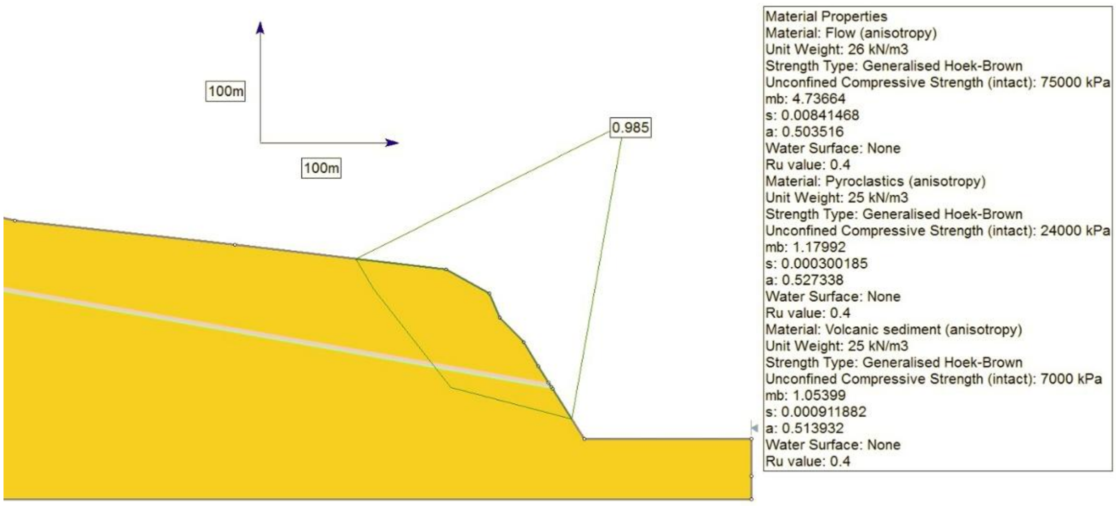


Figure 6 Output of minimum failure surface. The orange represents the Flow unit. The thin layers are Pyroclastics (beige) and Volcanic sediment (green).

4 DISCUSSION

The geomorphology of the amphitheatre is a low angle undulating grassy plain, which progressively gets steeper towards the back wall. Scree slopes exist near the Northern and Southern walls, while the inner amphitheatre consists of boulders of Flow material. The shape and size of the amphitheatre suggests block sliding occurring in a complex failure, mostly translational (potentially biplanar), thereby creating the steep side and back walls. The size of the Amphitheatre suggests that an estimate 25-30Mm^3 of material was involved in slope failure. Failures of coastal volcanic edifices are expected to fail on the seaward side due to lack of buttressing and active erosion on the base of the volcanic edifice (McGuire 2003). This appears to hold true for Mt Karioi where multiple amphitheatres (landslide scars) are present along the coast.

From the sensitivity analysis, the conditions of failure required a zone of weaker material strength values and high porewater pressures, with failure occurred along an anisotropy with a non-circular failure surface. Toppling failure, shown to be kinematically feasible is regarded as a process solely seen in small scale failures in this example (i.e. formation of the scree slopes), the amphitheatre geomorphology does not suggest toppling to be the main failure mechanism. One plausible scenario, related to the geomorphic conditions of the Te Toto Amphitheatre, is discussed below. It is assumed that the materials that filled the amphitheatre are that of the materials found from field mapping of the Southern and Northern walls.

The Te Toto stream, flows down the centre of the Te Toto Amphitheatre as a lineament. The lineation continues up to the top of Karioi as long thin gully. This may suggest a linear zone of weakness, in this case, a possible fault zone. There is limited field evidence for a fault at this site, the geomorphology shows a linear gulley leading up from the Te Toto amphitheatre up to the summit of Kairoi. Faulting has occurred in the region previously due to tectonic and magmatic activity, the geologic surface expression of fault movement may have been removed with failure of the amphitheatre. This stream may represent a central point of the failure, where 2 blocks separate and move towards the NNW and SW directions. The zone of weak materials and high porewater pressures could be explained by the following.

The fault would provide an ideal hydrogeological setting for groundwater to accumulate due to increased secondary porosity of the fault itself and fault damage in the form of cracks and decreased discontinuity (joint) spacing in the close surrounding materials (Caine et al 1996). Because of the weakened materials caused by the fault, it is feasible that a stream was also present at the time. The stream would create an eroded depression within the local geomorphology, acting as a catchment zone for surface water runoff. Achieving a 0.4 R_u value specified for failure by limit equilibrium, or even greater than, would be possible under this scenario after an intense or prolonged precipitation event.

5 CONCLUSION

The geomorphology of the amphitheatre suggests a low angle complex, possibly biplanar failure. Regional geomorphologic mapping shows similar expressions of slope failure around the region, but of a smaller scale than that of Te Toto. Recent failures are observed as a result of toppling failure, and their deposits are expressed as scree slopes near the Northern and Southern Walls; feasibility of the toppling mechanic is shown by kinematic analysis. Wedge failure and planar sliding were found to not be kinematically feasible. Three geotechnical units have been classified and mapped, including a Flow unit, Pyroclastics unit, Volcanic sediment unit. Rock mass strength parameters have been calculated for the Flow, Pyroclastics and Volcanic sediment units using intact material strength and GSI estimates. Intact material strengths were estimated using a combination of field observations, Schmidt Hammer and point load tests. The Flow unit displayed the highest rock mass strength and GSI, followed by the significant weaker Pyroclastics and Volcanic sediment units. The Flow unit represented the most volumetrically large unit. Discontinuities observed within the rock mass have variable orientations but can be broadly represented by 4 discontinuity sets.

Limit equilibrium modelling suggests that rock mass failure at the Southern wall will occur along a low angle bedding discontinuity, with elevated porewater pressures (R_u >0.4) and in a zone of material weakness. A cross-section parallel the southern wall was used for modelling geometry. Rock mass properties are modelled using Hoek-Brown and Mohr-Coulomb failure criterions. Low angle discontinuities were recognised in the field as bedding, and represented in limit equilibrium modelling using the generalised anisotropy function. The zone of weakness uses lower bound rock mass strength values from material strength estimation and GSI. Groundwater was included in the model by using R_u coefficients, from 0 (dry) to 0.4 (flowing), dripping groundwater was observed during fieldwork.

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