Spatio-temporal distribution of mass movements on Mount Maunganui, New Zealand

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ABSTRACT
Mount Maunganui is a rhyolite dome that stands 232 metres above sea level at the entrance of the Tauranga Harbour. In January 2011, Cyclone Wilma triggered several tens of landslides at this site. This study reviews the spatial distribution of the mass movement associated with the 2011 rainfall event and compares it to the landslide distribution since 1943. The limit equilibrium method was use to assess the slope stability conditions of a 2011 debris avalanche. The results demonstrate that slopes at Mount Maunganui are stable but that elevated pore pressure can lead to landsliding. The rock fall shadow angle of the furthest observed boulder was found to be 30-31° to the top of the initiation zone and 27-28° to the top of the talus. Using default restitution coefficients for “clean hard bedrock” and “soil with vegetation cover” materials, the software RocFall was able to capture the extent of the observed boulder field.

RÉSUMÉ
Le Mont Maunganui est un dôme de rhyolite à l'entrée du port de Tauranga qui s'élève à 232 mètres au-dessus du niveau de la mer. En janvier 2011, le Cyclone Wilma a causé plusieurs dizaines de glissements de terrain à cet endroit. Cette étude examine la distribution des glissements associés à l'événement de précipitations de 2011 et la compare à la distribution spatiale et temporelle des glissements de terrain depuis 1943. La méthode d'équilibre limite a été utilisée pour évaluer la condition de stabilité de pente pour une des ruptures de 2011. Les résultats démontrent que les pentes au Mont Maunganui sont stables mais que la pression interstitielle élevée d’eau peut initier des glissements de terrain. L'angle d'empreinte des blocaux le plus éloignée observée des éboulements rocheux se retrouve entre 30-31° lorsque mesuré du haut de la zone de départ et entre 27-28° lorsque mesuré du haut du talus. En utilisant les coefficients de restitution de défaut dans le logiciel RocFall pour les matériaux "socle dur sans débris" et "sol avec végétation", la modélisation numérique fut capable de capturer l'étendue du champ de blocaux observé.

1 INTRODUCTION

Mount Maunganui, traditionally known as Mauao, is an iconic feature of the landscape located on the east coast of New Zealand’s North Island. It also has significant value to both residents, tourists and for centuries as a Māori settlement (Wildland Consultants Ltd, 2004). Mount Maunganui is located at the entrance to the Tauranga Harbour, in the Bay of Plenty; seen in Figure 1. This 232 m high, steep-sided rhyolitic lava dome, is one of the most utilized national parks and archaeological sites in New Zealand, with 968,846 people using the park between July 2009 and June 2010 (Ray, 2012; Richards 1999).

The history of mass movements across Mount Maunganui is captured in historical aerial photographs dating back to 1943. These landslides have significantly altered the planform of Mount Maunganui in recent years. On the 29th January 2011 there was very intense rainfall (Figure 2); resulting in the failure of many slopes, causing about 80 mass movements with eight large landslides causing visible displacement of sediment and closing the trails (Tonkin and Taylor, 2011). Numerous mass movements which significantly damaged infrastructure in the Tauranga region in recent years have been the result of high intensity, short-duration rainstorms (Wesley, 2010). Landslides in both residual volcanic soils and rock masses in the Tauranga region are known to occur frequently, but there exist very few characterizations and analyses of these materials and their associated mass movements.

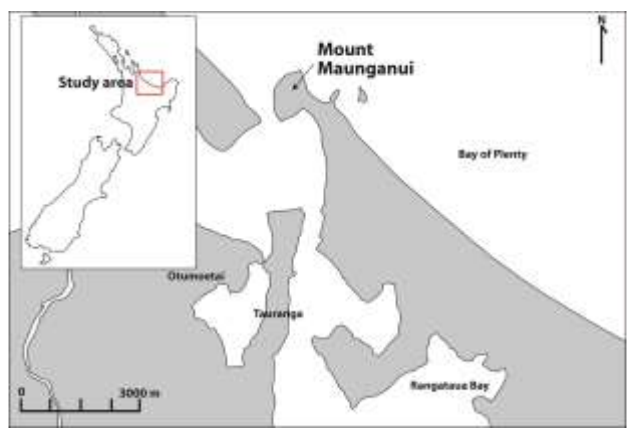

Figure 1. Location of Mount Maunganui on the North Island of New Zealand

1.1 Site description

Mount Maunganui is a rhyolitic dome formed by the upwelling and viscous outpouring of rhyolitic lava about

2.35 million years before present (Briggs et al., 2005). The Tauranga area has several other rhyolitic domes including Minden Peak, Manawata, and Kaikaikaroro (Briggs et al., 2005). The rocks are very strong to extremely strong (100 to >250MPa uniaxial compressive strength), but weathers to a very weak rock or firm clay (Richards, 1999). The rhyolitic flow bands clearly visible at the top and base of Mount Maunganui has a strongly foliated structure.

Mount Maunganui is a steep-sided-flat topped dome, made up of three parts; top, middle section and lower slopes (Hall, 1994). The top is made up of steep rhyolitic bluffs which have a prominent flow foliations that have a sub-vertical to vertical joint orientation; which are characteristic of structures at the vent (Hall, 1994). In the middle section, the slopes begin to become less inclined representing the top of a small inclined terrace. This section of Mount Maunganui has been used as pasture for sheep for more than 20 years. The lower slopes of Mount Maunganui are moderately inclined scalloped slopes which have are made up of thick residual volcanics soil on top of agglomerates with some flow band rafts present (Johnston, 1972). The base of the dome consists of highly eroded lava flows which extend out into the sea. The flow foliations of these lower flow bands varies from moderate to steeply inclined (Hall, 1994).

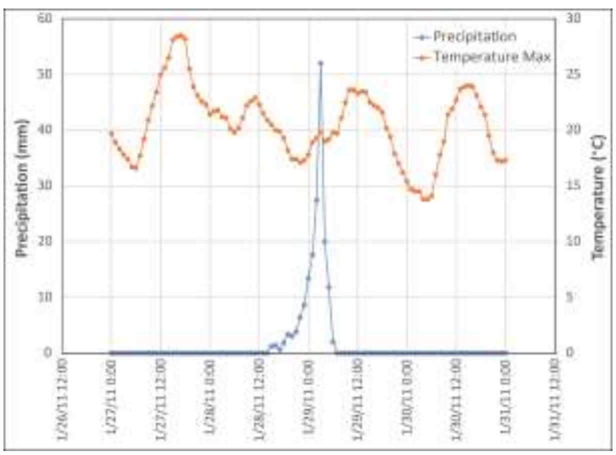

Figure 2: Hourly precipitation and temperature associated with Cyclone Wilma as recorded at the Tauranga Airport.

2 TYPE OF MASS MOVEMENTS

Four main types of mass movements have been identified at the study area. They include, rotational slides, debris flow, debris avalanche and rock fall.

2.1 Rotational slides

Rotational slides occur when the rupture surface is curved concave up and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Cruden and Varnes, 1996). A shallow circular failure refers to the depth extent of rotational movement that has occurred. Several shallow circular failures were observed in association with cuts along the walking trails (Figure 3A).

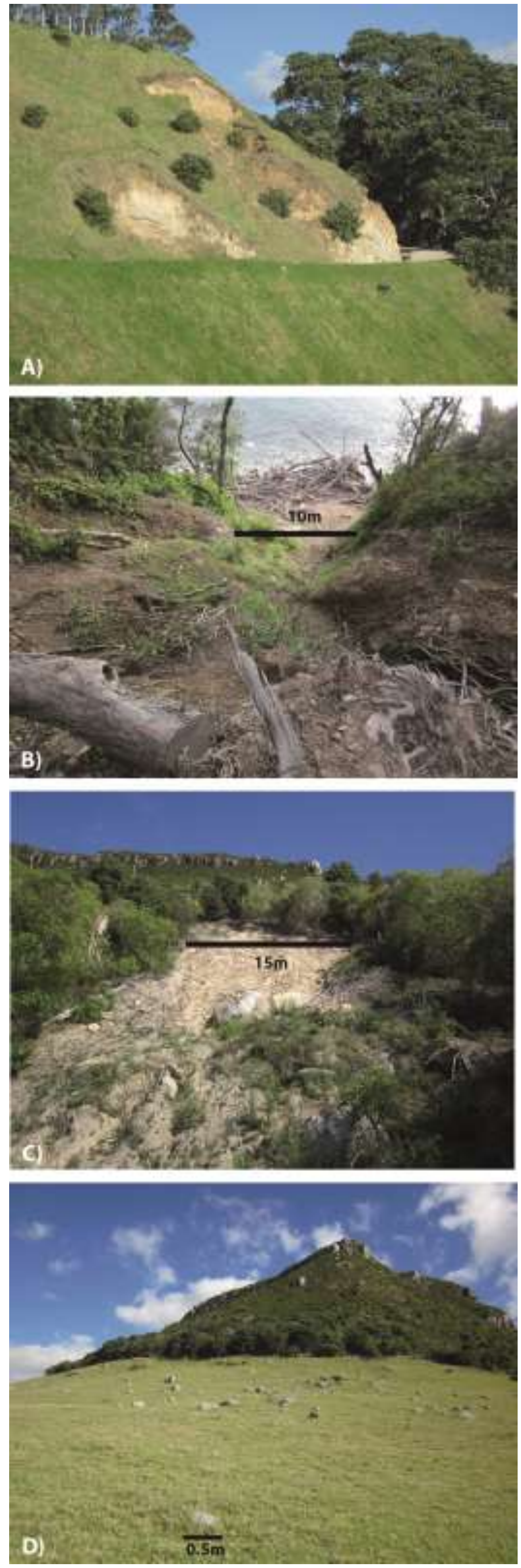

Figure 3. Landslide types observed at Mount Maunganui. A) Shallow circular slide, B) Debris flow, C) Debris avalanche, D) Rock fall

2.2 Debris flow

Debris flows are commonly caused by high precipitation and often occurring in valleys or gullies where there is a significant degree of confinement and at breaks in slope. These can be classified by the fan deposit at the base of the failure, comprising of fines sediments, large trees and boulders etc. They characteristically have a confined travel path (Hungr et al., 2001). There were three relatively short (100-200m runout length) debris flows identified on the west side of Mount Maunganui as part of this inventory (Figure 3B).

2.3 Debris avalanche

A debris avalanche is a type of mass movement in which a combination of soil, rock and water mobilize as a slurry that flows rapidly downslope (Cruden and Varnes, 1996). Debris avalanches comprise of more than 50% fine sediment and are also commonly the result of high precipitation events (Hungr et al., 2001). These failures have characteristically a shallow failure depth and they lack confinement along their travel path (Hungr et al., 2001). Several debris avalanches were observed on Mount Maunganui (Figure 3C).

2.4 Rock fall

Cruden and Varnes (1996) defined rock fall as the downslope movement via freefalling, bouncing, rolling and sliding of rock fragments (single block or several blocks not interacting with each other). Boulders (average size of 1 m x 1 m x 1 m) were observed in the lower slopes of the eastern half of Mount Maunganui (Figure 3D). Field observation at Mount Maunganui of the rock fall shadow angle of the furthest observed boulder was found to be 30-31° to the top of the initiation zone and 27-28° to the top of the talus. These values are consistent with previous observations in North America and Europe (compiled in Jaboyedoff and Labiouse, 2011).

3 SPATAL DISTRIBUTITON

The mass movements on Mount Maunganui were characterized temporally and spatially by building an inventory in GIS. This was done by digitizing landslides from aerial photographs available between 1943 and 2011. Their location could then be overlain onto a high resolution LiDAR digital elevation model (DEM) of Mount Maunganui which allowed the location of the landslides to be analysed in terms of their aspect and slope gradient.

The landslide inventory map for Mount Maunganui (Figure 4) shows a clustering of mass movements on the lower slopes in areas with little or no vegetation present. These slopes are steep with high sediment availability and the toes of these slopes in many places have been undercut and over-steepened by the construction of walking trails. The removal of the toes of these slopes with little or no vegetation resulted in widespread slope stability problems as seen in Figure 4. When the landslide inventory is overlain on the slope map, it suggests that the majority of the landslides initiation occurred at slope gradients between 18 – 32˚.

3.1 Soil properties

Soil samples in this study were characterised in two ways; their material properties, which was done using particle grain size analysis and mechanical properties, such as shear strength testing and Atterberg limits. In the field there were two main stratigraphic units identified from the head scarps of the soil mass movements; these were classified as sandy SILT (the upper unit, below the topsoil) and underlying this unit was silty CLAY (Figure 5). Samples could not be collected from Mount Maunganui for laboratory testing because of the heritage and cultural significance of this site to the local people. Alternatively, samples were collected from the following coordinates; 1884946E and 5816810N (NZTM grid); this site was identified from the geological map as having the same geology and the soil description as those on Mount Maunganui.

The silty CLAY unit has a plastic and liquid limit corresponding to 30% and 59% water content respectively. The remoulded silty CLAY unit was tested in a shear box at a moisture content of 40% (as collected in the field) and resulted in a cohesion of 45 kPa and a friction angle of 26° (Figure 6A). In turn the remoulded sandy SILT unit was non-plastic and was tested in the shear box at a moisture content of 13% (as collected in the field) which resulted in a cohesion of 1.2 kPa and a friction angle of 19° (Figure 6A). Samples were allowed to consolidate for 6 hours at each of the normal load investigated prior to testing, sample dilation during testing was not measured and the values reported are the effective cohesion and friction values of the material.

3.2 Rock mass description

The rock mass quality was assessed in the field using the geological strength index (GSI). The GIS quantifies rock masses in terms of surface conditions and structure of the rock (Marinos et al., 2005). The average rock mass quality observed at Mount Maunganui is plotted on Figure 7. The rhyolite flow toward the summit of Mount Maunganui has GSI values observed were between 40-55 due to the very blocky (4+ discontinuity sets, Figure 7 and Table 1) to blocky/disturbed/seam (weakly develop persistent flow bedding) rock mass structure and the good (rough) to fair (smooth) discontinuity surface conditions. The rhyolite agglomerate exposed at the base of the study site is disintegrated with fair surface condition resulting in GSI values between 25-35 (Figure 5).

Table 1: Summary of measured discontinuity set orientation and observed surface characteristics

Set	Dip (°)	Dip Direction (°)	Large Scale Roughness	Small Scale Roughness
1	80	253	Undulating	Rough
2	67	295	Planar and Undulating	Smooth
3	80	069	Undulating	Rough
4	72	155	Planar	Smooth and Rough
5	17	126	Undulating and Stepped	Smooth and Rough
6	22	314	Planar	Slickensided

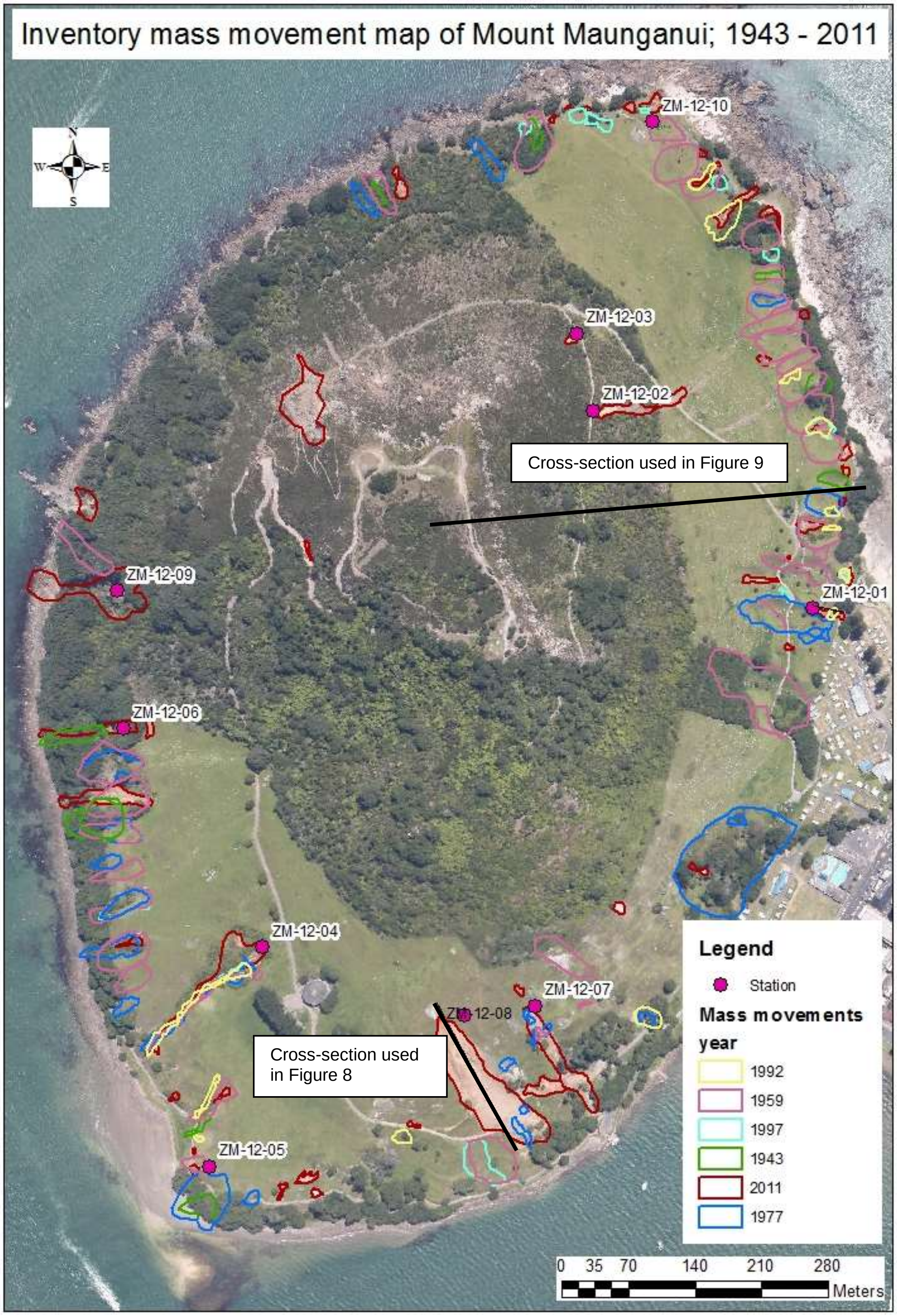

Figure 4: Spatial distribution of the landslide on Mount Maunganui between 1943 and 2011. Stations represent landslides that were described in details during the 2012 field season.

The rock strength of the rhyolitic flow deposits were measured using a Schmidt rebound hammer, this allows the strength to be quantified. Figure 6B shows the plots of the rebound values and observed frequency. The measurements were taken at five sites near the summit of Mount Maunganui. The average Schmidt hammer rebound value was 40.

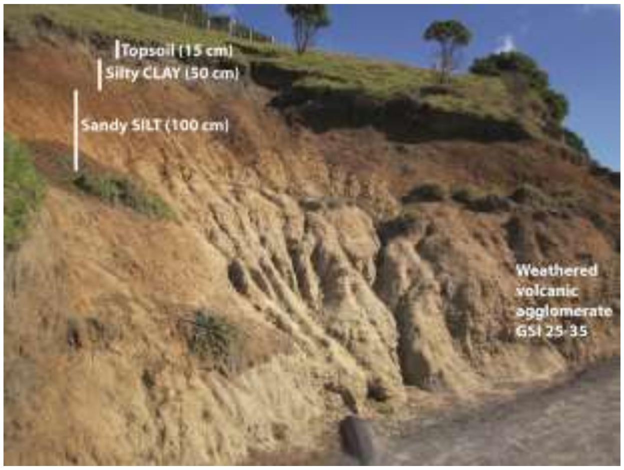

Figure 5: Soil stratigraphy observed at study site

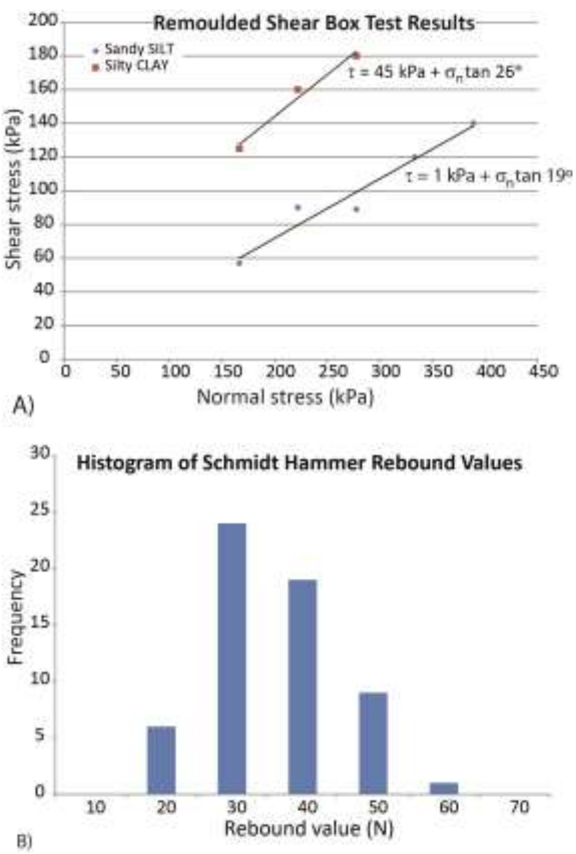

Figure 6 Estimated A) soil strength based on remoulded shear box test and B) rock strength based on Schmidt hammer rebound values.

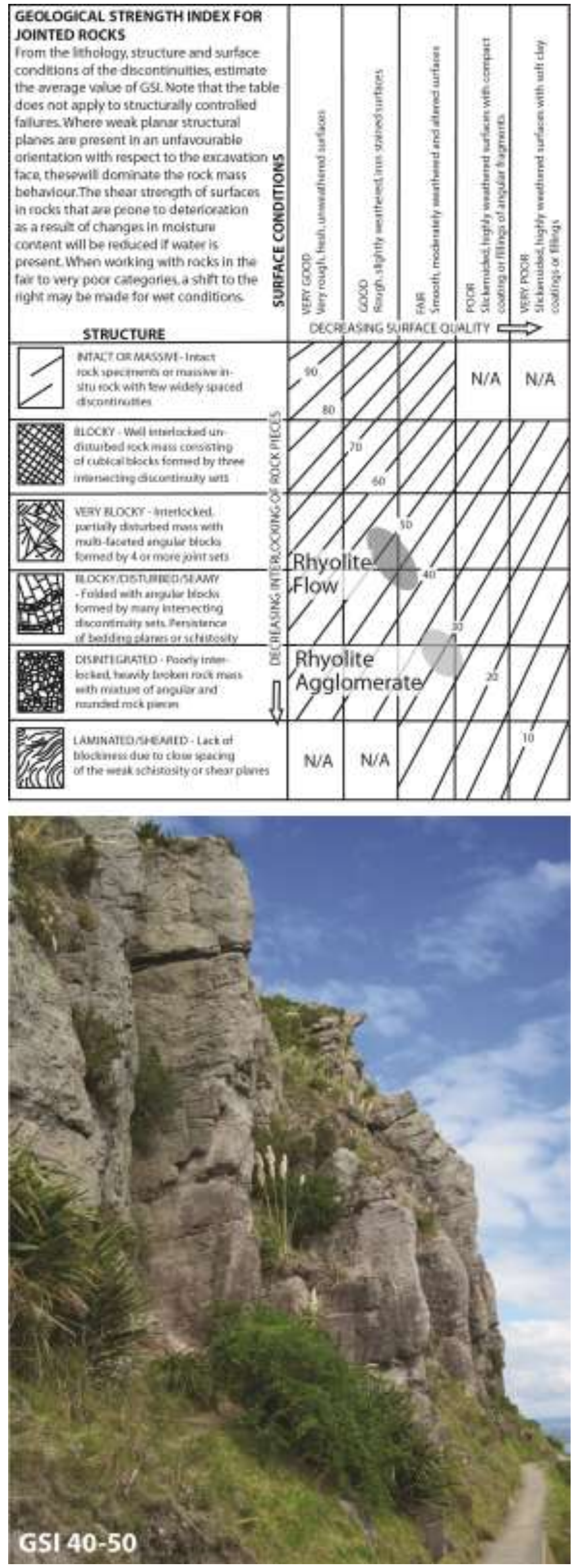

Figure 7: Distribution of the rock mass quality observed at Mount Maunganui and example of a representative rhyolite flow outcrop.

4 LIMIT EQUILIBRIUM

A slope stability analysis was conducted for one of debris avalanche (see Figure 4 for location) that failed during the January 2011 Cyclone Wilma using the software Slide (Rocscience, 2010). Slide uses the limit equilibrium method of slices to calculate a factor of safety (FOS). The model was constrained by the topography from the LiDAR DEM and material strengths derived from the shear box tests. The thickness of the top sandy SILT layer was based on field observations while the lower silty CLAY was assumed to extend to the base of the model as the bedrock was not observed at the case study. The results of the analysis suggest that the slope investigated were stable (FOS>1) in their dry state (Figure 8) and unstable when simple conceptual pore water pressure representations (Ru = ratio between pore water pressure and the overlying weight of the soil column) was included. These models represent conservative analyses as they applied the remoulded strengths of the soil horizons identified. In-situ soil strength is expected to be higher due to soil structure, undisturbed soil cohesion, and root reinforcement.

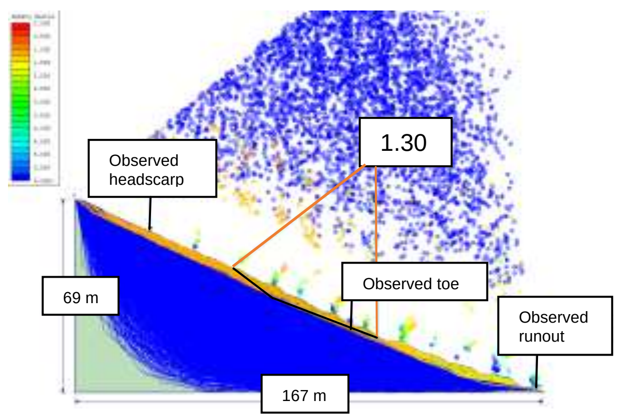

Figure 8: Non-circular limit equilibrium analysis assuming fully drained condition at a 2011 debris avalanche. See Figure 4 for location of the cross-section used.

5 ROCFALL MODELLING

RocFall is a 2D rock fall runout program by Rocscience (2008). It provides a statistical representation of the energy, velocity, and travel path down a slope for a given range of block size. The user can specify the dimension of the block, its starting velocity, the topography of the slope and the properties of the ground over which they travel. Due to the variable nature of topography and the material properties a statistical distribution can be specified for each input parameter used in RocFall. The analysis is conducted for a user defined number of rock blocks. Figure 9 shows the travel path and end-point of 1000 modelled block. The blocks were assumed to be 1 m^3 based on field observation in the runout zone. The travel path material properties used were the default values for clean hard bedrock in the upper part of the slope, soil with vegetation in the lower section. The modelled runout distance corresponds very closely to the field observation with the rock fall boulders stopping on the lower grassy terrace of Mount Maunganui. The good correspondence between the model and observed rock fall runout as demonstrated with a similar shadow angle (31°) obtained in the model as observed in the field (30-31°). This suggests that the default material values in RocFall will provide representative travel distance for similar geology and surficial material in the Bay of Plenty.

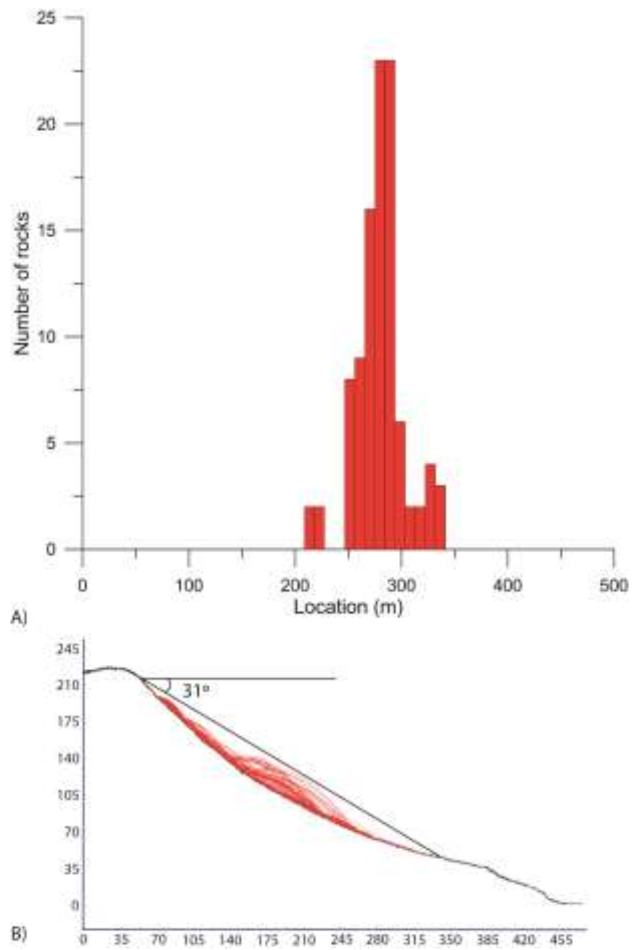

Figure 9: Rock fall modelling assuming a start zone at the A) Histogram of modelled boulder end-point, B) Cross-sectional profile showing the runout path of 1000 simulated boulders (see Figure 4 for location of cross-section)

6 DISCUSSION

General observations can be made about the spatio-temporal distribution of the mass movement types on Mount Maunganui. There is a concentration of shallow-circular slides in the south-western and north-eastern sides at the base of Mount Maunganui. These lower slope failures make up the majority of mass movements throughout the 68 year inventory. There has also been a reoccurring history of debris flows that occur predominantly at breaks in slopes (natural and anthropogenic) and as a result of significant rainfall events, combined with drainage confinement. The debris flows do also occur on the lower slopes of Mount Maunganui but are controlled by the increased groundwater flow at these changes in slopes. The occurrence of mass movements in the upper section of Mount Maunganui appears to be mostly restricted to the 2011 events according to the inventory mapping and they consist mostly of debris avalanches.

The inventory mapping and field investigation of mass movements at Mount Maunganui suggested that they are being influenced by several contributing factors; sediment availability, land use, rainfall and the flow paths of surface- and ground-water. Land use has been recognised as a very important factor that influences the nature and occurrence of rainfall triggered mass movements (Glade, 2003). There has been strong correlation between rainfall-triggered landslides after deforestation; this has been found to have a one to two decade lag time followed by an increase in landslides in areas of deforestation (e.g. Glade, 1998; Jakob, 2000; Guthrie, 2002). Mount Maunganui has a long history of anthropogenic land modification which has change through time. The rhyolitic dome was once a Māori settlement; the remnant of which is still visible in the form of trenches, ridges, and middens (Wildland Consultants Ltd., 2004). In the last 20 years Mount Maunganui has been used as pasture for sheep, along with the addition of a maintained network of walking trails and associated surface water drainage structures. Repetitive fires, including the most recent one on the northern slopes in 2003, are an additional process that influences the vegetation and by association the slope stability conditions at this site.

Mass movements induced by high intensity rainfall events is well researched topics (e.g. Caines, 1980; Crozier, 1999; Jakob and Weatherly, 2003). It is recognised that infrequent, high intensity rainfall events promote wide scale instability and numerous mass movements (De Rose, 2012). The Mount Maunganui mass movements associated with the January 2011 Cyclone Wilma were triggered by a rainfall event that is close to the reported rainfall thresholds of hill country suggested by Glade (1998) for the Wellington, Wairarapa and the Hawke's Bay regions in New Zealand. The 2011 Cyclone Wilma precipitation at the study area was lower than values from Glade (1998). This is most likely due to the highly sensitive nature of the volcanic soils on Mount Maunganui; requiring less rainfall to promote instability (Wesley, 2007; Keam, 2008).

7 CONCLUSIONS

This paper presented the results of a landslide inventory for Mount Maunganui on the North Island of New Zealand. A spatial and temporal evaluation of this inventory showed that there is a concentration of shallow-circular slides and debris flows in the lower slopes, with few debris avalanches on the mid to upper slopes; rock falls were observed to initiate from the flow banded rhyolites at the summit. The susceptibility of the residual volcanic soils to instability is a widespread problem on Mount Maunganui and on other rhyolitic domes in New Zealand. The lack of vegetation and the exposure of the slopes to the weather indicate ongoing instability issue on this rhyolitic dome with sensitive soils remaining vulnerable to high intensity rainfall events and continued farming of much of the slopes.

The two main soil stratigraphic units identified were a silty CLAY and sandy SILT; these were sampled and characterised by their material properties and the particle size analysis confirmed these field sample classification. The shear testing of the silty CLAY found to have a cohesion value of 45kPa, and a friction angle of 26˚, there was also Atterberg limits analysed for this sample which gave a plasticity index of 30% and a liquid limit of 59%. Shear box testing of the sandy SILT, gave a cohesion value of 1kPa and a friction angle of 19˚.

Limit equilibrium slope stability analyses were used to assess the effect of groundwater on a recent mass movement. The results of the analyses suggest that the slope investigated was stable (FOS>1) in its dry state and unstable (FOS<1) when simple conceptual pore water pressure representations (Ru) was included. This is consistent with observation that most mass movements are associated with rainfall events. The rock fall runout modelling, using the software RocFall, captured the extent of the observed boulder field. This suggests that the default material values in RocFall can provide representative travel distance for similar geology and surficial material as Mount Maunganui.

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