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Mudslides as a Mechanism for Long-Term Creep on Waitemata Group Rocks

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Abstract: On Tawharanui Peninsula numerous mudslides are formed in soils developed on Waitemata Group flysch. Mudslides consist of slow-moving shear failures typically formed on weak sedimentary materials, and are characterised at Tawharanui by disturbed ground in the source areas, discrete, boggy track zones, and low-angled debris fans. A geomorphic model developed sees failure occurring on flat-lying Waitemata Group strata, where failure of saturated soil occurs along a basal shear surface defined by the regolith / bedrock contact. Simple stability analysis of a shallow, circular failure supports this geomorphic model. Modelling suggests critical conditions for failure initiation require slope angles of 15° to 20°, within the range of slopes measured. Dimensions of the failure predicted vary with assumed bedrock depth: for a weathered zone thickness of 6 m and slope angle of 20" the failure is 289 m long, in agreement with an average measured length of 303 m. It is clear that mudslides affect much of the Tawharanui Peninsula and have the capacity for long-term creep.

INTRODUCTION

Mudslides are identified as the predominant form of mass wasting presently occurring on the Tawharanui Peninsula, north of Auckland. The Tawharanui Peninsula is on the east coast of the North Island, approximately 50 km north of Auckland City (Figure 1). Slopes in the area are subdued, with long, gentle slopes (typically 13 – 15 °) grading into flat, swampy areas at the coastal margins. Pastoral farming is the predominant landuse, so evidence of soil movement is preserved. The underlying bedrock is Waitemata Group flysch, with a thick cover of residual soil formed on the Waitemata Group rocks. This paper presents evidence for mudslides on the Tawharanui Peninsula, describes the characteristics of these features, and presents initial modelling data to assess the conditions under which mudslides may develop.

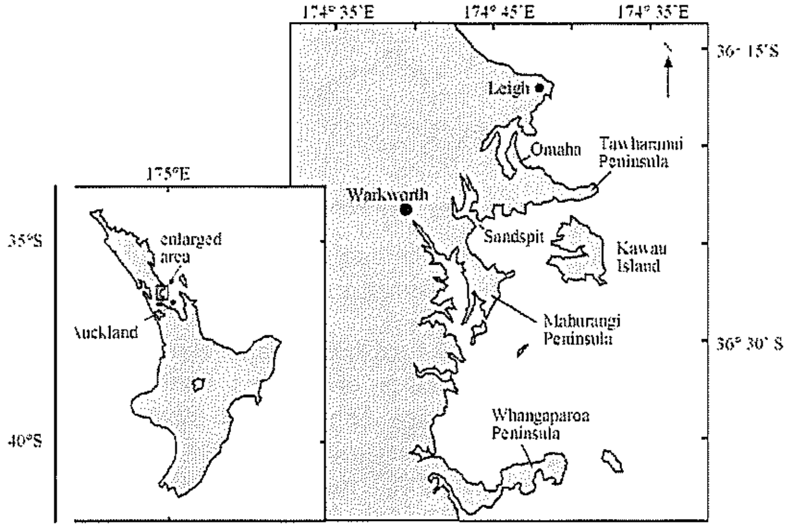

Figure 1. Location Map.

MUDSLIDES

Mudslides (or earthflows) are common, relatively slow-moving forms of shallow mass wasting on weak sedimentary materials. They have been recognised in other parts of New Zealand, particularly in the Gisborne and East Cape regions (Eyles, 1983; Wasson and Hall, 1982; Zhang *et al.,* 1991a,b, 1993). Mudslide morphology typically consists of three components:

> a source area that forms a basin or bowl shaped zone containing failure scars, zones of debris accumulation, and often disturbed groundwater patterns (Brunsden, 1984);
>
> a track which is generally a well-defined channel through which the material passes from the source to the accumulation zone – the size and shape of the track depends upon the nature of the materials and the geomorphology of the area (Brunsden, 1984); and
>
> an accumulation zone which is generally a low-angled, lobate feature formed from one or more lobes of debris (Brunsden, 1984; Chandler and Brunsden, 1995).

Many mudslides are more complicated in morphology, and consist of a complex of multiple tracks and poorly-defined source areas (Zhang *et al.,* 1991b; Blong and Goldsmith, 1993). Movement is predominantly by sliding on discrete side and basal shear surfaces, and source areas and tracks are typically separated from surrounding ground by sharp shear zones (Brunsden, 1984; Brunsden and Ibsen, 1996). Rates of movement range from rapid movement, to slow movement over decades (Zhang *et al.,* 1991b; Bisci *et al.,* 1996), and often vary due to fluctuating pore water pressures (Hutchinson and Bhandari, 1971; Allison and Brunsden, 1990).

GEOMORPHOLOGY

Mudslides are by far the most common form of mass movement recognised on the Tawharanui Peninsula, with some 30 single or complex mudslides identified (Figure 2).

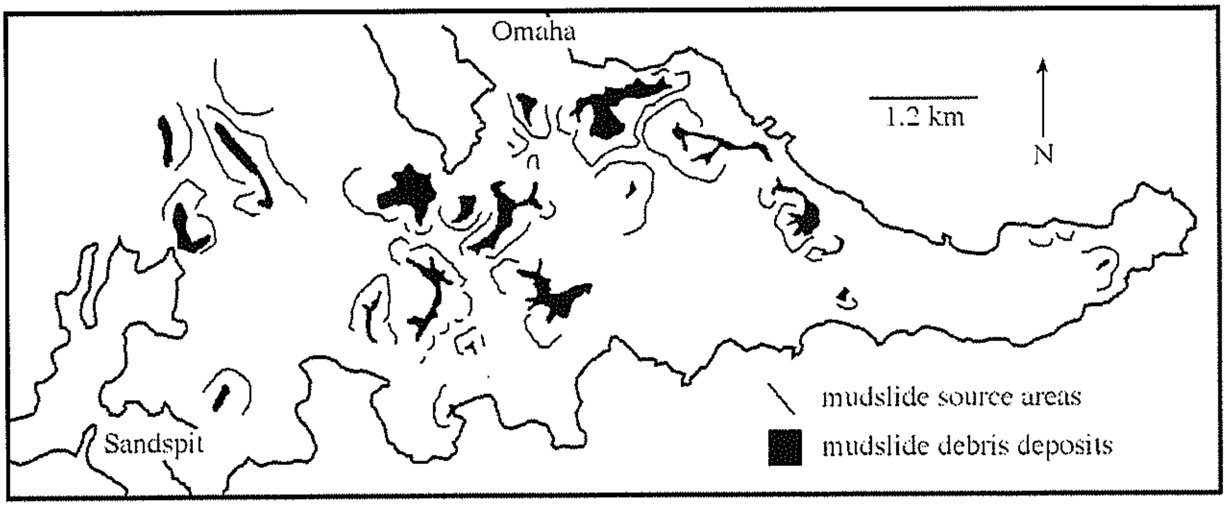

Figure 2. Distribution of mudslides on the Tawharanui Peninsula identified from aerial photograph analysis. Lines indicate headscarps of single or complex mudslides; black areas are depositional zones.

Source areas characteristically consist of subdued headscarps surrounding bowl-shaped areas of disrupted ground, often shown by stepped surfaces, or cracked, disturbed turf (Figure 3). In some cases (Figure 4) these are relatively small, discrete zones, but in most instances the source areas of several mudslides coalesce into complex zones occupying the bulk of the valley heads (Figure 3). These source areas have an average width of 407 m, length of 303 m, and aspect ratio of 0.7. Considerable variability in the size measurements exists, probably because many of the recognised source areas are actually complexes of several individual mudslides. Numerous reeds on the steeper portions of the valley sides attest to high water contents of the soils in the source areas of the flows.

The tracks occupy most of the valley floors, which are broad, smooth, flat-lying areas generally covered in reeds (Figures 3 and 4). These contain only small, ephemeral streams (if any). The tracks are marked by a sharp reduction in slope angle at the edges; typically they do not show extensive cracking or disruption of the material in the track zones. Estimates of track length are difficult as many tracks represent coalescence of debris from a number of source areas. Measured track lengths range up to 1050 m and have aspect ratios of 1 to 14 with an average of 4.2. The measured track length in this environment is strongly controlled by the position of the source with respect to the coast, so these measurements reflect location rather than mechanism.

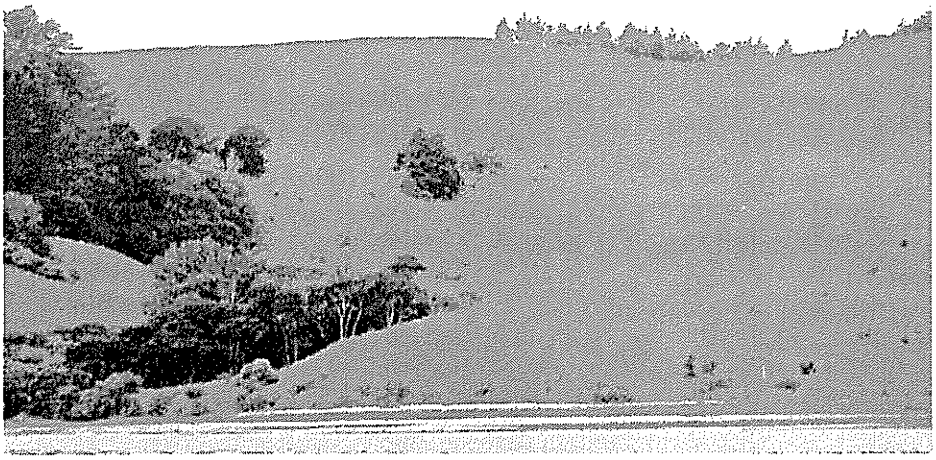

Figure 3. Disturbed ground surface characteristic of mudslide source areas. The track of this feature extends under the trees in the lower left of the photo, and discharges directly into the estuary. Active movement is apparent from turf rolls along the coastal margin in this area.

The accumulation zones are mostly within the coastal area, and are thus removed or masked by coastal processes before any large lobes are developed. Small depositional lobes exist at the base of some slopes (Figure 4); these form characteristically low-angled fans with very poorly drained soils.

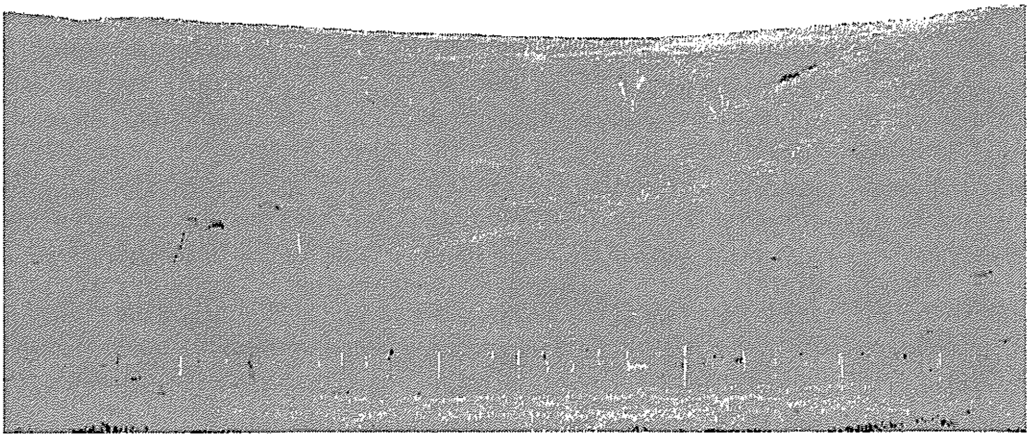

Figure 4. A small mudslide in Tawharanui Regional Park. The source area consists of a bowl-shaped depression with several zones of disturbed ground supplying debris to the track. No single failure can be discerned, but disturbed ground is apparent and the trees are stressed. The track extends from the base of the source area and merges into a low-angled depositional fan. Only a small, ephemeral stream exists in the track, but characteristic wetness is indicated by reeds.

MATERIALS

Geology is predominantly Waitemata Group sandstone and siltstone sequences, with basement greywacke in the eastern portion of the peninsula, and Recent alluvial sediments in low-lying areas (Hopgood, 1960; Thompson, 1961). Waitemata Group rocks in this area consist typically of flat-lying (bedding plane dip < 5 °) dominantly sandstone beds up to 3 m thick interbedded with thin (0.1 m) siltstone beds. Sandstone layers are weak, with continuous, widely-spaced (> 1 m), vertical joint sets.

Residual soils are developed on the Waitemata Group rock materials. The depth to the base of the weathered zone is poorly defined: values of the thickness of the weathered zone (depth to bedrock) for similar Waitemata Group materials in Auckland City are commonly 5 – 7 m (Chapman, 1998), which is consistent with observations of regolith thickness (5 - 10 m) in coastal sections of the Tawharanui Peninsula. No comprehensive dataset regarding the geotechnical properties of these soils from the Tawharanui Peninsula is available. However, compilation of data presented by Macleod (1988) and Chapman (1998) pertaining to soils derived from Waitemata Group rocks in Auckland City shows average values of (error estimates represent ± 1 standard deviation):

42 ± 6 % clay, 53 ± 4 % silt, and 5 ± 4 % sand
Plasticity Index (PI) = 28 ± 8 %, activity = 0.7 ± 0.2
saturated bulk density (p) = 1730± 80 kg m^{-3}; porosity (η) = 21 ± 5 %
peak shear strength: $c = 9 \pm 2$ kN m^{-2}, $\phi = 26 \pm 7°$
residual shear strength $c_r = 12 \pm 5$ kN m^{-2}, $\phi_r = 18 \pm 5°$

These characteristics indicate very high clay content soils, which commonly include smectite and other swelling clays. This is likely to give restricted permeability, and the capacity to expand and contract with changing moisture content. Recent literature highlights the variability of residual soil geotechnical parameters for the Auckland soils, with plasticity index values ranging from 16 – 50 % (Pender *et al.*, 2003), and peak shear strength values c' and ϕ' ranging from 7 - 35 kN m^{-2} and 22 – 38" respectively (Terzaghi, 2003). The data compiled here are in keeping with this wide range of published values, the peak friction angle compares favourably with 'typical' results quoted by Pender *et al.* (2003) of c' = 22 kN m^{-2} and ϕ' = 24'. The cohesion value is low compared with this typical value, but within the range suggested by Terzaghi (2003).

MODELLING

Waitemata Group strata underlying the Tawharanui Peninsula are flat-lying with widely-spaced joints. Restricted permeability both within the non-jointed sandstones, and within the clay-rich soil materials, results in poorly drained surficial weathered and soil materials. However, large proportions of active (swelling) clays lead to the development of contraction cracks during dry periods that may allow ready access of water into the soil. These conditions allow for rapid infiltration of water into cracked soils, with very slow drainage out of the soil profile. The regolith materials thus can easily become saturated, as indicated by reeds growing high on many of the slopes. Failure of saturated soils along a basal shear surface defined by the regolith / bedrock contact is thus believed to be a likely model for the process observed. This type of failure is envisaged to be very shallow compared with the length.

The qualitative model above is based on geomorphic evidence alone. The following sections describe the results of basic stability analysis modelling using the parameters defined above. The aim of the modelling at this point is to investigate the plausibility of the geomorphic model developed, and to establish likely conditions at initial failure of these features. It is not intended to give a precise, site-specific analysis of an individual failure, as the available data do not allow this. Limit equilibrium slope stability modelling was undertaken using GALENA™ (Clover Technology, 2001). By undertaking a series of analyses, calculations of combinations of slope angle and thickness of the weathered zone for critical (F = 1.00) conditions were achieved.

Input Parameters

The aim of the modelling undertaken was to establish likely failure conditions for initiation of mudslide movement. Thus, peak soil strength values were used. No modelling of continuing movement of an already-existing failure was considered as the data are inadequate for this. A circular failure model was employed (Bishop Simplified Model). A straight, uniform slope was assumed, with soils with the above properties lying over stronger bedrock (Figure 5). Slope angles used in the analysis ranged from 10" to 20" (which brackets the typical mid-slope angles of 13 – 15° measured) in order to investigate the sensitivity of the factor of safety to slope angle. Measured slope lengths reach up to 350 – 400 m, so these lengths were allowed for in the modelling. In order to bracket the range of likely weathered zone thicknesses, values for this parameter from 2 – 12 m (at 2 m intervals) were considered. Water is recognised as an important contributor to mudslide movement. In order to examine the sensitivity of these slopes to fluctuations in water table levels, analyses were undertaken with water tables ranging from dry (water table below bedrock / weathered zone boundary) to saturated (water table at ground surface) at 2 m intervals.

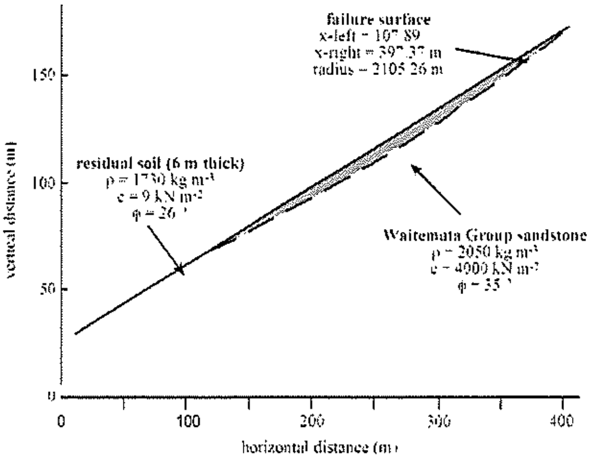

Figure 5. Mudslide model used in stability analysis. The failure surface shown is the critical (lowest factor of safety) surface for the conditions given.

For each weathered zone thickness considered, factors of safety were generated for all combinations of slope angle and water table depth. A critical surface search using wide restraints was undertaken for each analysis in order to generate the lowest F value for each combination of conditions. In each case examined it was notable that the failures all extended to the base of the weathered zone, indicating that this provides an important control on the stability of these slopes.

Results

Graphs of factor of safety versus water table depth were plotted for each weathered zone thickness and slope angle combination. Best-fit second-order polynomial regression equations were fitted to the resulting curves (regression coefficients (R^2) in all cases were 0.999 or greater). Only combinations for which critical conditions were reached were included in this analysis – 2 m and 4 m thick weathered zones generated factors of safety greater than 1.00 for all conditions considered, so were excluded from further analysis. Using the equations derived, combinations of slope angle and water table depth that generated critical (F = 1.00) conditions were calculated for each weathering zone thickness. Suitable combinations were plotted to give a family of predictive lines (Figure 6).

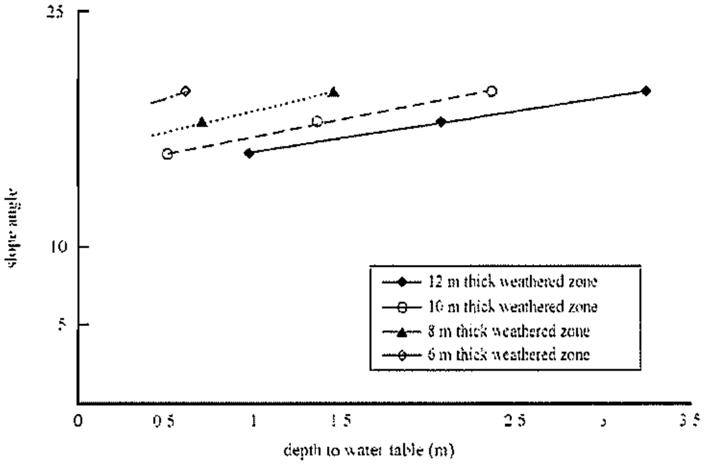

Figure 6. Slope angle, water table depth, and weathering zone thickness combinations that produce critical (F = 1.00) conditions.

It can be seen from Figure 6 that critical conditions required to initiate slope failure include slope angles of approximately 15° to 20°, which are slightly greater than the typical slope angles measured for slopes in the area. It is also clear that as the thickness of the weathered zone increases, the slope angle at which critical conditions are reached reduces, and the depth to the water table at which failure can be initiated increases significantly for any given slope angle. Thus, with increased weathering and the extension of the weathering front to greater depths, previously stable slopes can be brought to critical conditions, often with relatively deep water tables.

There are many assumptions in this analysis, especially as the local material strength properties are not well defined. However, the predicted nature of the failure and the conditions for failure initiation are sufficiently close to the present-day situation that we are confident that this mechanism is realistic. The failure model predicted is of a very shallow, circular-type failure that shears along the contact with the bedrock (Figure *5)*. Exact dimensions of the failure predicted in each model vary according to the assumed bedrock depth, but for a thickness of weathered zone of 6 m and a slope angle of 20" the failure produced is 289 m long. This agrees well with the average measured length of 303 m for the mudslides observed in the area.

RATES OF MOVEMENT

Rates of movement on these mudslides are not known, nor are the times of initiation of the movement. We know of no obvious indicators of extremely rapid movement, such as damaged fences and structures. It is clear that some mudslides move more rapidly than others in that the source areas are clearly delineated by broken and disrupted ground, but the actual rates of movement cannot be established at this stage. Likewise, the time of initiation of these failures cannot be firmly established with available data. Mudslides occur in areas of pasture; this may suggest that the mudslides post-date deforestation (evidence from the East Cape area suggests that mudslides are more active under grass than trees (Zhang *et al.,* 1993)) which occurred in the mid to late 1800s. However, the existence of charcoal often associated with early Maori occupation at the base of some mudslide deposits suggests that many at least are much older than European settlement.

HAZARD

Due to present land-use patterns, the mudslides described in this paper currently represent little risk to infrastructure on the Tawharanui Peninsula. Most of the area is farmed, and the recent rate of movement of the failures appears to have only a small impact on the farming practices. Clearly some ground is disturbed in the source areas, but this has limited effect on pasture growth. The track and accumulation zones may suffer from bogginess, but again this has only nuisance value. Where houses and other structures have been built on mudslides, the potential for risk is greater, as mudslide movement, even at slow rates, may impact significantly on building foundations and structural integrity. At present however, the area of the Tawharanui Peninsula that is developed in this way is small, and the overall risk is thus low.

Historical research by Bisci *et al.* (1996) identified 12 reactivations of a 5.4 km mudslide in Italy since the 16th century, with most reactivations correlated with periods of intense and persistent precipitation. It is recognised that movement rates are strongly dependent on soil moisture content and hence often vary seasonally (Brunsden and Ibsen, 1996); the work by Bisci *et al.* (1996) suggests that longer-term climatic fluctuations may be more important than seasonal water balance for mudslide evolution.

Precipitation in New Zealand varies at a range of time scales (Plummer *et al.,* 1999; Manton *et al.,* 2001; Salinger, 2001). Global warming may also alter precipitation patterns, with the consensus view suggesting that global warming is likely to result in warmer temperatures and an increased frequency and intensity of precipitation for the study area (Ministry for the Environment, 2001). Of relevance to the potential mudslide hazard is the occurrence of periods of increased precipitation, both in terms of higher frequency and intensity. These periods are conducive to saturated conditions that can reactivate or accelerate mudslide movement. Further, increased precipitation and warmer temperatures should accelerate weathering within the regolith and hence may destabilise slopes susceptible to mudslide development. Insufficient data exist to determine current rates of weathering, and any acceleration due to global warming, so that it is difficult to assess the potential risk. However, the potential exists for reactivation and increased mobility of mudslides due to natural or anthropogenic climatic change.

CONCLUSION

This study has identified a mechanism of mass movement operating in an area where it was previously unreported in the published literature. At this stage we do not know the rates of movement, or frequency of pulses of activity, nor do we know the age of these features. However, it is clear that mudslides affect a large proportion of the Tawharanui Peninsula, and have the capacity for long-term creep. Such creep processes can be highly destructive over the lifetime of any structures. Reactivation or increased mobility of mudslides due to climatic change represents an increased hazard for infrastructure in the region. Knowledge of the rates of movement of these failures is necessary in order to fully assess the hazard they pose.

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