Controls on slope failure and erosion in weak rock to strong soil in the coastal escarpment west of Matata, New Zealand

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ABSTRACT
Landslides and high rates of erosion along cliffs of the coastal escarpment west of Matata, New Zealand, damaged a major transportation corridor, which includes Highway 2, a railway route, and properties. The cliffs are primarily composed of stiff clayey silts, compact sands and gravels, and extremely weak marine and terrestrial sedimentary and pyroclastic rocks. These weak and erodible deposits are highly susceptible to failure during intense and prolonged rainfall events, which causes rock fall, debris avalanches, piping, and rilling. Each of these is caused by different combinations of material properties and exposure, and each process in turn promotes specific hazard conditions.

1 INTRODUCTION
The coastal escarpment near Matata, New Zealand (Fig. 1) is developed in young (< 400 ka), highly laterally variable sequence of marine and terrestrial sedimentary and volcanic soils. Cliffs along the escarpment were cut during 125 ka and 7 ka sea-level high stands, but are now separated from the active beach front by a prograding accumulation of sediments from nearby rivers. The May 2005 debris flows at Matata were accompanied by numerous additional slope failures along this coastal escarpment. The combination of these failures, together with two major debris flows sourced in the stream catchments south of Matata, caused damage to 87 properties and closed Highway 2 and the railway for many days (McSaveney *et al.*, 2005).

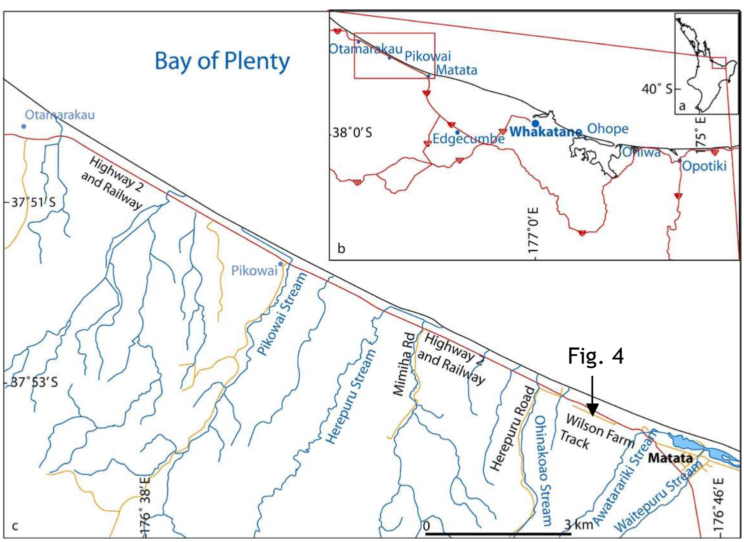

Figure 1 - Map Showing location of field area and geographic features of note.

2 GEOLOGY
The stratigraphic sequence near Matata has been previously described by Healy and Ewart (1965). The base of the Matata sequence is a fining upwards, approximately 15 meter thick succession of gravels, sands, and clayey silts. The gravels are clast supported, gap graded sandy gravels composed primarily of greywacke cobbles. The sands are moderately graded and well compacted. Despite its tight packing, this sand is highly susceptible to fluvial erosion and in outcrop this sand can be easily scooped out by hand without tools. Geotechnical tests on representative samples of

the clayey silt give a UCS value of 435 kPa, cohesion (c) of 300 kPa, and angle of friction (φ) of 21°. These clayey silts are moderately plastic (PL ~20) when remolded. Ring shear tests to determine residual shear strength parameters, obtained values of 50 and 30° for c and φ respectively, indicating that this soil material is moderately sensitive to disturbance. Although this clayey silt material classifies as a soil under most schemes (e.g., NZ Geotechnical Society, 2005), it forms overhanging cliffs and tends to fail by rock fall along fractures. A primary volcanic unit,Tephra A, occurs within the clayey silt and is a 1-1.5 metre-thick well graded and compacted pumice gravel. Tephra A is normally included in failures of the clayey silts that lie above and below it (Fig. 2), but does not itself contribute to the failures. A further 5 meters of clayey silt (upper clayey silt) overlies Tephra A. This clayey silt grades upwards into a 15 to 20 metre-thick unit of nearshore marine and terrestrial sands, with a high content of crystal and pumice fragments. A 10 metre-thick sequence of reworked pumice sands and gravels interbedded with organic rich clayey silts overlies these sands.

Above this sequence is the 280 ka Matahina ignimbrite (Bailey and Carr, 1994; Houghton et al., 1995), a well-graded and tightly packed sandy pumice gravel. Further inland from this field area, the Matahina ignimbrite is moderately welded rock with columnar joints. The top surface of the Matahina ignimbrite is eroded to form paleovalleys, and in many places along the cliffs the ignimbrite has been completely removed. A highly variable and poorly exposed sequence of terrestrial sands, clayey silts, and paleosols, informally called the Pikowai beds by Bailey and Carr (1994), unconformably overlies the post-Matahina erosion surface. Following a further period of erosion and valley incision, the 61 ka Rotoiti ignimbrite and Rotehu ash (Wilson et al., in press) were deposited. The Rotoiti ignimbrite is a well graded, moderately to poorly compacted gravelly pumice sand, and the Rotoehu ash a thinner poorly compacted pumice and crystal sand. Some thinner pyroclastic deposits gravels, sands and silts overlie the Rotoiti but these beds are laterally variable and discontinuous, and do not affect slope stability.

Debris flow deposits are preserved at the mouths of valleys where streams leave the steep land to flow through the coastal plain and into the ocean. Reworking of these deposits (which appear to be of late Pleistocene to Holocene age from the ages of blanketing tephras) plus influxes of fluvial sand have formed a 50-150-m wide coastal plain on which the road and rail links are situated.

3 MASS MOVEMENT AND EROSION

A number of erosion processes involving different mass movement styles are active in various parts of the coastal escarpment, in addition to 'background' frittering of cliff faces. The four major processes noted during this study are: (1) rock fall due to undercutting by flowing water, (2) shallow debris avalanches related to shaking and precipitation events, (3) deep incision of rills by concentrated overland flow, and (4) piping failures due to concentration of groundwater flow.

Figure 2-Rock Fall in Awatarariki Stream. Scale bar is approximately 3 m.

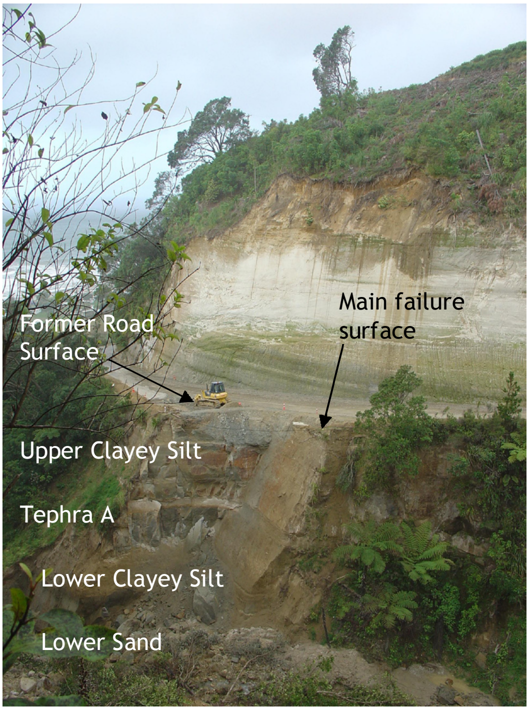

Figure 3- Landslide from 2005 floods below Herepuru Road. Ohinekaoa Stream bed and the sand layer are visible in the bottom of the picture. Tephra A is ~ 1 m thick.

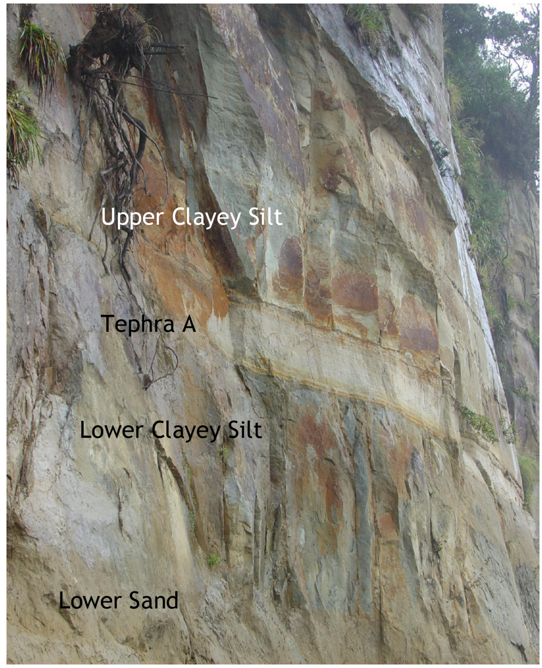

Figure 4- Failed surface along Herepuru Road from moderate storm in 2006. Fracturing and oxidation of clayey silt is evident. Lower sand is exposed at the base of the photo. Tephra A is ~ 1 m.

3.1 Rock Fall

As noted in Section 2, the clayey silt below Tephra A is underlain by the easily erodible lower sand. When the contact between the sand and silt deposits is exposed near a stream or road level, slope failures become ubiquitous. As stream water or rainfall drainage flows along the face of the exposure, it removes the sand, undercuting the clayey silt or "mudstone". Soon after undercutting, a slab of this material will drop or slide off of the cliff face, usually along fractures. In some cases, smaller blocks will regularly fall from the face, rather than a single catastrophic failure (Fig. 2). According to the classification of Cruden and Varnes (1996), these landslides classify as active, retrogressive, complex, rapid to very rapid, moist to wet, rock slide–falls.

This style of erosion poses the greatest hazard to Herepuru Road, located 3 km west of Matata (Fig. 1). At this site, erosion of the sand layer mentioned above by the Ohinekaoa Stream, which runs generally parallel to the road, has caused rock falls that undermined or removed the road platform in 2005 (Fig. 3). Further east, surface drainage at the side of the road is sufficient to cause erosion of the same sand unit and to trigger rock falls onto the road surface (Fig. 4). Maintenance costs of this road are extraordinarily high (circa $2M: data from Whakatane District Council) relative to the number of people the road serves (six families).

3.2 Debris avalanches

In the coastal area, debris avalanches generally occur from pumice gravels near the top of the cliffs. When dry or damp, these units exist in a metastable state. High pore water pressures due to heavy and prolonged precipitation or seismic accelerations have overcome the cohesion of the deposits and sent them avalanching downslope. These debris avalanches are moderately erosive, and tend to incorporate organic material, residual soil, and some weaker *in situ* material as they move. These landslides generally classify as active, complex, rapid to very rapid, moist to very wet, debris flow–debris falls (Cruden and Varnes, 1996). The term "debris avalanche" is used to indicate that these landslides are not confined to channels, but instead flow rapidly in a nearly straight line down slope until they deposit their loads at the base of the cliffs (Fig. 5).

Figure 5 - Typical debris avalanche originating in pyroclastic deposits near the top of the cliffs. Flow path and deposits are also shown. Railroad crossing sign is approximately 2.5 m high. Location noted on Fig. 1.

3.3 Rills

Farther west than about 5 km from Matata, the cliffs are dominantly composed of exposures of the Matahina and Rotoiti ignimbrites. In these locations, concentrations of overland flow have incised deep rills into the pumice sands and gravels. In some cases, these rills could be described as proto-canyons with vertical walls and flat floors. Although not a form of landsliding, this type of erosion could threaten properties located on top of the cliffs.

3.4 Piping and Aquitards

The two major ignimbrite units in this area were erupted over a pre-existing incised topography. In the case of the Rotoiti, it was deposited on top of a moderately developed paleosol or impermeable sediments. These sediments or the paleosols act as aquitards, preventing water from percolating further downwards and forcing groundwater to flow along the contact between the overlying pyroclastic material and the paleosol. During periods of intense and prolonged rainfall, pore water pressures can build near the cliff face until a catastrophic piping failure occurs (Fig. 6). This process can propagate through the materials, leaving large voids underground. In some cases, they will propagate up to the surface as *tomos* (a local word for sinkholes of this type).

Figure 6 - Large piping failure in Rotoiti ignimbrite. This pipe formed as a catastrophic failure during the May 2005 storm that also caused debris flows in Matata. See person for scale.

4 DISCUSSION AND CONCLUSIONS

The coastal escarpment west of Matata consists of marine and terrestrial sediments and pyroclastic deposits. These strong soils and/or extremely weak rocks are frequently susceptible to catastrophic erosion. The soils exposed in this area show properties transitional from weak rocks to stiff and hard soils. Rock fall, debris avalanches, rilling, and piping dominate in different areas of the escarpment depending on material properties, exposure, and contact geometry.

The geological conditions in this area contrast with those at the headrace canal site of the Ruahihi power scheme in Tauranga that suffered a catastrophic slope failure in September 1981 (Burns and Cowbourne, 2003). Although the rocks are of similar age, there is a significant difference in the geometry of bedding planes in the coastal escarpment at Matata. In the case of Ruahihi, the wall of a paleovalley dipped out of the face of a large fill downslope of the canal. This paleovalley wall was marked by a clay-rich, highly sensitive paleosol, which concentrated groundwater flow and led to piping and slide-flow failure of the canal wall (Prebble, 2001). The materials at Ruahihi are highly sensitive. Field shear vein measurement of peak and residual strength are different by a magnitude of 50 (Prebble, 2001), whereas laboratory determinations in the Matata area show sensitivity magnitudes of only 5. Another major contrast is the geometry of contacts. In the coastal escarpment at Matata, paleovalleys are generally perpendicular to the cliff face and thus lack the geometry required to cause deep-seated rotational or translational slumps and slides.

Along Herepuru Road erosion of an exposed weak sand within the clayey silt exerts the primary control on rock fall. In many locations, this stratigraphic sequence is repeated by faulting, causing the sand bed to be repeatedly exposed to fluvial erosion. This is most obviously the case on Herepuru Road where slopes above the road are vegetated and more gently inclined where the mudstone is exposed at road level. When the sand is exposed at road level, the slopes are barren and near vertical through continued undercutting and failure.

Debris flow and avalanche hazards pose the greatest risk to the railroad and Highway 2. Piping failures are a possible additional mechanism to the generation of shallow debris avalanches in the cliffs. The larger piping failures are catastrophic, but dependent on a number of conditions that do not seem to occur frequently in the coastal escarpment. These have not developed to the same extent or generated catastrophic debris flows similar to those seen in Naples, Italy, in similar deposits (Del Prete et al., 1998).

Rilling features are common, but pose little or no risk to the transportation corridor. The primary hazard associated with rilling is loss of property due to cliff retreat. Catastrophic failure is unlikely, and the hazard is easily avoided by placing buildings further back from the cliff edge.

Mitigation of these hazards must begin with further information about the rock and soil units that comprise the coastal escarpment. Further geomechanical and field work are underway to clearly define the behavior and distribution of these materials.

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