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Landslide Typology in the Eastern Bay of Plenty – Implications for Risk Management of Road Infrastructure

P. Martins, J. Griffiths
Beca Ltd, Tauranga.

P. Horrey
Beca Ltd, Christchurch.

D. Legaspi
Waka Kotahi New Zealand Transport Agency, Auckland

ABSTRACT

The State Highway network in Eastern Bay of Plenty crosses terrain with varied geomorphology and geology with a range of landslide types presenting a major geological hazard. This paper presents examples of recent landslides that have affected the highway network, including the underlying geological factors controlling landslide typology, and risk management approaches adopted under the Bay of Plenty East Network Outcomes Contract. The landslides typically had complex failure mechanisms dominated by translational rock slide components, occurring in Early Cretaceous greywacke, Late Tertiary sandstones and Early-Middle Pleistocene alluvial and marine sediments. Staged risk management strategies, which were often influenced by movement reactivations, included visual and survey monitoring, reactive and/or pre-emptive controlled operation of highway operation, and temporary or long-term engineered solutions.

1 INTRODUCTION

The Eastern Bay of Plenty has a highly varied geology and geomorphology, ranging from Pleistocene alluvial and marine sediments in coastal cliffs around Ōpōtiki, to bush-clad steep Cretaceous greywacke hills through the Waioeka Gorge. With approximately 600km of State Highway network crossing steep country, landslides are a common geological hazard to the road infrastructure. This paper is based on the experience gained with the Bay of Plenty East Network Outcomes Contract, during which a number of highway-blocking landslides have occurred followed by risk mitigation measures to keep the highway corridor flowing. The landslides described in the paper are listed below and their locations are indicated in Figure 1:

- **SH2 Son of Midway rock slide**: translational rock slide, wedge failure in Early Cretaceous greywacke
- **SH2 Twin Faces landslide**: shallow rotational / translational rock/debris slide in Early Cretaceous greywacke with very closely spaced discontinuities
- **SH35 Maraenui rock slide**: translational rock slide in weathered Early Cretaceous greywacke
- **SH35 Runaway rock slide**: translational rock slide, planar failure in Late Tertiary sandstones;
- **SH2 Waiotahi earth slide**: shallow translational earth slide in Early-Middle Pleistocene alluvial and marine sediments

Figure 1: Location of landslides described in this paper.

Risk management strategies during initial response and remedial stages include:

- Monitoring of sites: visual, manual survey monitoring and electronic/telemetered systems
- Reactive and/or pre-emptive controlled operation of the highway: single lane operations, daylight only traffic, full closures
- Engineered solutions:
  - Temporary: light blasting, scaling, heli-sluicing, concrete barriers, temporary rockfall fences
  - Long-term: slope reprofiling (earthworks), road realignment, rockfall protection structures.

2 LANDSLIDES AND RESPECTIVE RISK MANAGEMENT STRATEGIES

In this section, five landslides occurred in the Eastern Bay of Plenty are described. The terminology used for landslide classification follows Varnes (1978) and Cruden & Varnes (1996). The characteristics of each of the landslides are outlined, including the underlying geological factors, followed by the risk management measures applied to keep the road corridor flowing.

2.1 Translational rock slide, wedge failure in Early Cretaceous greywacke

2.1.1 Landslide characteristics

The Son of Midway rock slide is located on SH2 in the Waioeka Gorge, between Ōpōtiki and Gisborne, at Route Position 334/6.40 (Waka Kotahi NZ Transport Agency, 2004). At this location, and through most of the Waioeka Gorge, the road traverses the hillslope through cutting and sidling fill. The hill affected by the landslide is around 400m high with a general slope angle of 50°.

The initial failure occurred in the afternoon of 7 July 2017, releasing about 3000 m^3 of rock debris. The failure progressed overnight between 7 and 8 July 2017, releasing approximately more 5000 m^3 of debris. These failures were triggered by sustained rainfall in the10-day period prior to the them, including two events in excess of 115mm/24h.The combined failures completely engulfed the highway (Figs 2a, 2d), leading to a full closure of seven days and one lane operation for approximately 14 days. Subsequent smaller failures (but larger than 100 m^3) occurred during winter and spring 2017. The last known relatively large (> 100 m^3) failure occurred on 24 June 2018. Smaller failures continue to occur on a regular basis.

The landslide can be classified as an active, retrogressive, multiple rock slide, with extremely rapid (> 5 m/s) rates of movement. This is a wedge failure, controlled by bedding (150/59 dip direction/dip) and a joint set (272/45), plus a tension crack on the back (222/75) (Figs 2b, 2e).

The failed rock mass consists of weak to moderately strong, slightly weathered, greywacke comprising 0.3-1.0 m thick sandstone beds interbedded with 0.1-0.3 m thick mudstone beds. Bedding and two main joint sets are steeply to very steeply inclined, closely to moderately widely spaced.

Figure 2: SH2 Son of Midway rock slide. (a) first failure on 7-8 July 2017; (b) general view of the landslide after removal of the debris; (c) helicopter sluicing following the initial failure; (d) road level view of the first failure on 7-8 July 2017; (e) road level view of the wedge failure.

2.1.2 Risk management strategy

Given the possibility of further failures affecting the site, the following measures were adopted to manage the risk to the clean-up crews initially and then to road users:

- **Initial "make-safe" stage:** helicopter and UAV visual monitoring, helicopter sluicing of loose debris still sitting on the slope (Fig 1c), light localised blasting of relatively large unstable blocks still attached to the slope, hand scaling of smaller blocks.
- **Short-term solution:**
  - **First stage:** UAV and road-level visual monitoring, terrestrial laser scanner monitoring, installation of temporary concrete barriers, use of spotters, single lane operation under good weather and daylight only, pre-emptive closure of the highway under severe weather warnings.
  - **Second stage:** installation of a temporary rockfall fence, construction of a temporary lane on the rock slide debris (i.e. realignment of the road away from the landslide face), two lane operation.
- **Long term solution:** currently being developed.

2.2 Shallow rotational / translational rock/debris slide in Early Cretaceous greywacke with very closely spaced discontinuities

2.2.1 Landslide characteristics

The Twin Faces Landslide is located on SH2 in the Waimana Gorge, about 12km south of Whakatāne, at Route Position 258/5.50. At the site the road was built through cutting and sidling fill. The hill is around 130 m high with a general slope angle of 45°.

The initial failure occurred on 8 August 2016 and was relatively small, releasing about 100 m^3 of debris. Following ex-tropical cyclone Debbie on 6 April 2017, when more than 200mm of rainfall were recorded for a 48-hour period, a much larger failure occurred releasing approximately 2000 m^3 of debris. A further failure occurred on 14 April 2017, following ex-tropical cyclone Cook. These two failures entirely blocked the highway (Fig 3a), leading to full closure of the road for a number of weeks while remedial works were undertaken (further discussed in section 2.2.2).

The geology of the site consists of weathered greywacke mantled by pyroclastic fall deposits up to approximately 10 m thick. The rock mass can be described as moderately strong to strong, highly to moderately weathered, homogeneous mudstone (greywacke). Discontinuities are randomly oriented and very closely to moderately widely spaced. The pyroclastic deposits consist of interbedded layers of clayey silt, silty sand and sandy gravel, where the coarse particles are often pumiceous.

The 2017 failures were of translational mode and involved mostly the pyroclastic cover sliding on top of the underlying rock. Subsequent smaller failures (but larger than 100 m^3) occurred during winter 2018, this time involving rock from the lower parts of the slope.

On 5 July 2019 another failure occurred, this time mobilising the lower two-thirds of the slope, entirely through rock (Fig 3c). A 1m headscarp was formed, extending nearly across the full width of the slope. Whilst the failure mobilised a large volume of material, the amount of debris that dropped onto the road was relatively small (a few hundred cubic meters). This failure was largely translational, but had a minor rotational component, with the head of the landslide slightly tilting back.

As a summary of the events so far, the landslide can be classified as an active, enlarging, successive shallow rotational/translational rock/debris slide, with very slow (16 mm/year **-** 1.6 m/year) to extremely rapid (> 5 m/s) rate of movement.

Figure 3: SH2 Twin Faces landslide. (a) failure on 6 April 2017 following ex-tropical cyclone Debbie; (b) reprofiling of the top (pyroclastic cover) following the 2017 failures; (c) 5 July 2019 failure through rock, involving the lower two-thirds of the slope; (d) telemetered and conventional monitoring system installed on the slope following the 2019 failure.

2.2.2 Risk management strategy

Given the nature of the 2017 failure, the initial measures were adopted:

- **“Make-safe” stage (2017):** helicopter and road level visual monitoring, helicopter sluicing, clean-up with long reach excavator from the base.
- **Engineered solution (2017):** top-down slope reprofiling of the top of the slope through the failed section in pyroclastic materials.

Then in 2019, as detailed in the previous section, the landslide evolved (as often large landslides do), requiring a new risk management approach. The following measures were implemented:

- **Make-safe” stage (2019):** UAV and road-level visual monitoring, conventional survey monitoring, light localised blasting, installation of temporary concrete barriers, use of spotters, single lane operation under good weather and daylight only, pre-emptive closure of the highway under severe weather warnings.
- **Long term solution:** telemetered slope monitoring system with near-real time alerts (Fig 4d), rockfall attenuator (currently being built).

2.3 Translational rock slide in weathered Early Cretaceous greywacke

2.3.1 Landslide characteristics

The Maraenui rock slide is located on SH35 along the coast between Ōpōtiki and Cape Runaway, at Route Position 28/4.65. The rock slide affected a cut slope in a new section of SH35 built in 2010-2011 to bypass a section of the road which was irreparably damaged by a large landslide between Aug/2009 and Dec/2010. Details of the original failure and the road realignment are discussed by Read et al (2012) and Read et al (2013). The cut slope is around 45 m high, with an angle of 40°.

Initial small (< 100 m^3) failures started to occur in the week commencing 14 September 2015. These failures continued to happen for the following two weeks, until a large failure occurred in the early hours of 2 October 2015. The trigger to these failures was a three-week period of sustained rainfall, including three events in excess of 60mm/24h. This large failure released around 1000m^3 of debris, completely engulfing the road (Figs 4a-4c). The failed material continued to move for the following days, leading to nearly one week of full and/or partial closure of the road. Smaller failures continue to occur since then, leading to occasional partial closures of the road.

Figure 4: SH35 Maraenui rock slide. (a) oblique view of the site following the main failure; (b) front view of the landslide; (c) top view of the landslide – note the pronounced tension cracking at the head of the landslide; (d) detail of tension cracking at the head of the landslide.

The failed rock mass consists of weak to moderately strong, highly to moderately weathered greywacke, comprising thinly bedded mudstone and localised moderately thin beds of sandstone. Bedding and one main joint set are very steeply inclined to subvertical, very closely to extremely closely spaced. Additional randomly oriented, closely spaced discontinuities also occur. The failure is of translational mode, with the nearly homogeneous failed material sliding on top of less weathered greywacke, likely controlled by relict structure.

The landslide can be classified as an active, retrogressive, multiple rock slide, with very slow (16 mm/year - 1.6 m/year) to rapid 1.8 m/h – 3 m/min) rate of movement.

2.3.2 Risk management strategy

Given the possibility of further failures affecting the site, to manage the risk to the clean-up crews initially and then to road users, the following measures were adopted:

- **Make-safe" stage:** UAV and road-level visual monitoring, installation of temporary concrete barriers, use of spotters, single lane operation under good weather and daylight only.
- **Long term solution:** the design for reprofiling the slip was completed in early 2016 but, given that no further large failures occurred, it was decided not to implement it. Concrete barriers remain in place, with visual inspections carried out yearly.

2.4 Translational rock slide, planar failure in Late Tertiary sandstones

2.4.1 Landslide characteristics

The Runaway rock slide is located on SH35 along the coast between Ōpōtiki and Cape Runaway, at Route Position 106/9.02, close to the boundary between the Bay of Plenty and Gisborne regions. The main failure occurred on 24 July 2018, extending through the whole height (approx. 20 m) of the cliff adjacent to the to the highway (Fig. 5a). The failure was triggered by heavy rainfall in the previous 24 hours, associated with sustained rainfall over the previous two weeks. The failure released approximately 1000 m^3 of rock debris, completely blocking the road. A secondary, smaller (< 20 m^3) failure occurred on 7 August 2018. No significant failures are known to have occurred since then.

The landslide can be classified as a dormant, retrogressive, multiple rock slide, with extremely rapid (> 5 m/s) rate of movement. The failure was of planar type, controlled by a joint set dipping approximately 45 degrees towards the road and a subvertical joint set acting as tension cracks (Fig. 5c).

The failed rock mass consists of weak to moderately strong, slightly weathered, massive, light yellow sandstone and thinly bedded, light brown mudstone. Bedding is generally sub horizontal, and there are two systematic joint sets: one steeply inclined and very widely spaced, and one subvertical and widely spaced (Fig 5b).

2.4.2 Risk management strategy

Given the nature of the landslide, the following measures were adopted:

- **"Make-safe" stage:** helicopter and road level visual monitoring, implementation of local detour route, localised light blasting of relatively large unstable blocks still attached to the slope (Fig. 5d), hand scaling of smaller blocks.
- **Long term solution:** implementation of catch ditch at the base and conventional survey monitoring.

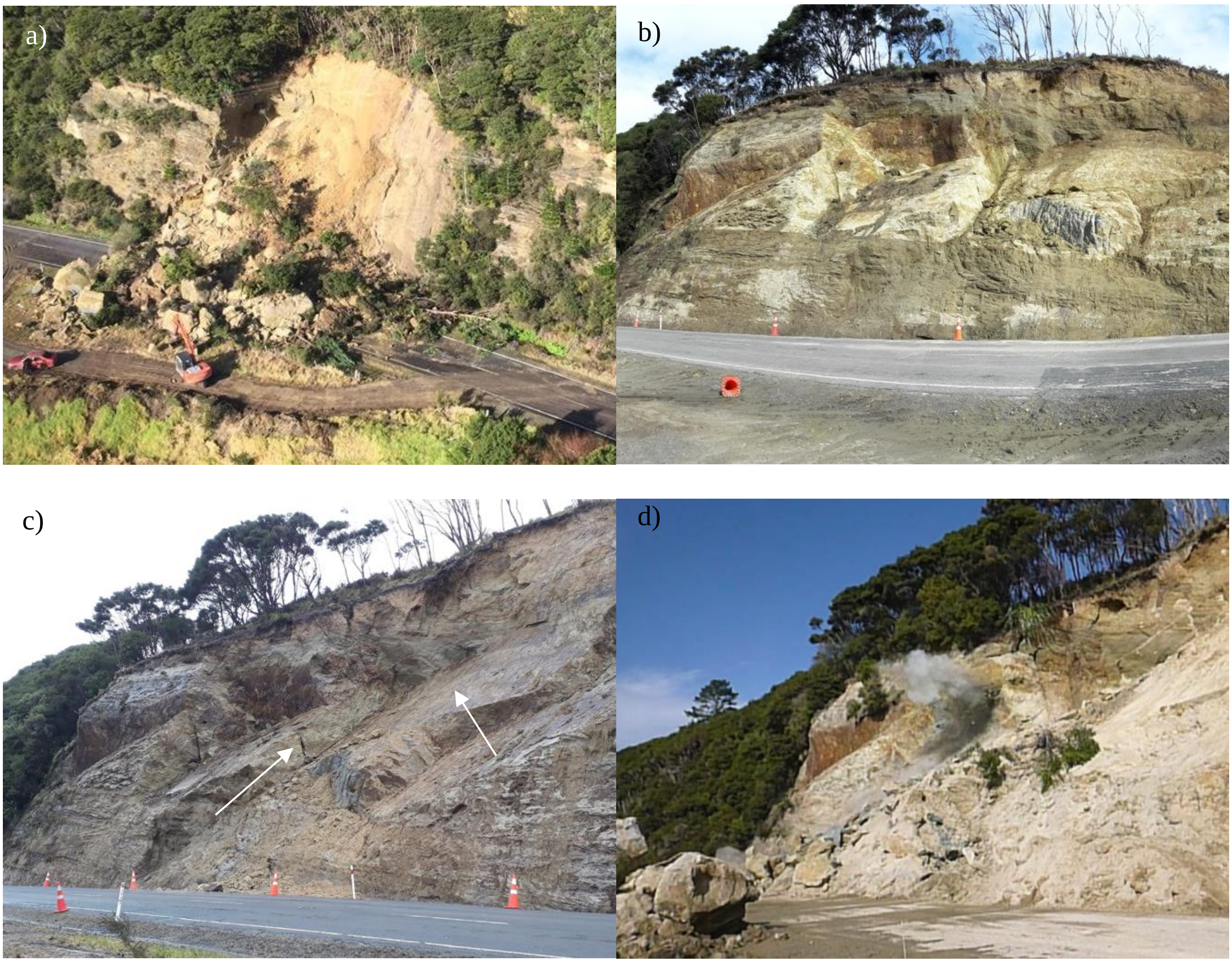

Figure 5: SH35 Runaway rock slide. (a) oblique view of the site following the main failure; (b) site after clean-up completed; note the light brown mudstone at the base of the slip and the light yellow sandstone at the top; (c) discontinuity sets controlling the planar failure; (d) light blasting applied as part of the "make safe" stage.

2.5 Shallow rotational earth slide in Early-Middle Pleistocene alluvial and marine sediments

2.5.1 Landslide characteristics

The Waiotahi earth slide is located on SH2, about 8km west of Ōpōtiki, at Route Position 294/2.35. This section of SH2 was built as an embankment through the dune field, at the toe of the coastal cliffs (Fig. 6b). The cliffs are up to 70m high and are formed of pumice-rich, interbedded alluvial and marine sediments of early to middle Pleistocene age. These cliffs have a recurrent history of failures of various sizes.

Anecdotal evidence suggests that the last relatively large (i.e. extending through the whole height of the cliff) failure happened in the early 2000's. As part of the remediation of that failure an approximately 10m high reinforced buttress fill was built at the toe of the slip. No further details are known about the failure.

On 3 March 2018 the top third of the cliff failed, releasing 200-400 m^3 of soil and closing the road (Fig. 6a). A second failure occurred on 3 September 2018, this time involving the lower half of the cliff (Fig. 6c). This second failure released 3000-5000 m^3 of, completely engulfing the road. The material mobilised in the 2018 failures consist mainly of fine to coarse pumiceous sand with some fines and minor boulders, cobbles and gravel. No further failures are known to have occurred since September 2018.

The landslide can be classified as a dormant, retrogressive, multiple shallow rotational earth slide, with very rapid (3 m/min - 5 m/s) to extremely rapid (> 5 m/s) rate of movement.

Figure 6: SH2 Waiotahi earth slide. (a) March 2018 failure, view from the top; (b) March 2018 failure, general site view; (c) September 2018 failure.

2.5.2 Risk management strategy

Following the 2018 failures, the site was inspected from above and from road level. Because of no visual evidence of impending further failures or loose material on the cliff, it was assessed that it was safe for the clean-up crews to start working as soon as weather improved.

Once the failed material was cleared from the road it was confirmed that the existing toe buttress was not damaged. At this point the risk to road users at the Waiotahi landslide was assessed as similar to that of other sections of the road at the toe of the wider cliff. Consequently, no additional measures were taken other than adding the site to the register of sites that are subject to annual geotechnical inspections.

3 DISCUSSION

The examples presented in this paper are of landslides that affected the State Highway network, therefore the primary objective of the risk management strategies adopted for each of the sites was to safely maintain an acceptable level of service to road users. This involves balancing risk, cost and impacts on the communities affected by these landslides. The development of the various risk management strategies was based on, and limited by, project requirements at the time immediately following the failures (esp. considerations on quick re-opening of the road and cost).

Understanding landslide typology, especially size and likelihood of further failures, triggering mechanisms and rate of movement is key to the development of practical risk management strategies: How frequent can further failures be expected? How much debris is likely to be involved? What is the nature of the debris? How quickly and at what velocity can the debris reach the carriageway?

Equally fundamental is understanding the road environment impacted by the landslides, as well as the regional traffic network: Is there enough sight distance for drivers to take corrective action if they see a failure underway and/or debris on the lane? What is the average daily traffic? Is there room to implement control measures within the road reserve? Is the route a lifeline? Are there any detour options? How long are they? Can the detour route accommodate all types of traffic (heavy, overdimension, etc)?

The largest landslides affecting the state highway network in the Eastern Bay of Plenty tend to occur in the greywacke hills of the Waioeka Gorge, due to the height of the landforms and high rainfall rates. This is the case of the Son of Midway rock slide described in this paper, as well as a number of other failures, including the very large Sandy Slip occurred in 2012 (Read & Jennings, 2013). It is important to note though that large landslides happen is other parts of the Eastern Bay of Plenty, such as the debris flow that affected Matatā in 2005 (McSaveney et al, 2005) or the original failure that forced the realignment of SH35 at Maraenui hill (Read et al, 2012; Read et al 2013).

A common feature to all landslides described in this paper is that rainfall, concentrated during one/two days and/or sustained over one or more weeks prior to the failure, is the main triggering factor. All of the failures are associated with rain events with an annual recurrence interval (ARI) not higher than two years. This means that further failures can be expected at reasonably frequent events in the future and therefore risk management measures are required.

SH2 through the Waioeka Gorge is the main passenger and freight route between the Gisborne and Bay of Plenty regions. A length of approximately 60km without practical detour routes (the shorter detour adds around 400km), an alignment characterised by short sight distances and a high susceptibility to landslides make the Waioeka Gorge the main hotspot for risk management and road resilience in the Eastern Bay of Plenty.

All the landslide and road environment factors mentioned above had to be balanced in the development of the risk management strategies for the various sites discussed in this paper. Typically, a staged approach was required, but the specific sequencing and duration of each stage were directly influenced by the landslide and road environment factors.

For sites where a local detour option was not feasible, such as the Son of Midway site, the immediate priority was to safely reopen one lane of traffic under very controlled conditions, to then progress onto the next remedial stages. Whereas for sites where a local detour existed, such as the Twin Faces site, the focus was to progress as much as possible while the corridor was still closed, to quickly move onto more permanent remedial measures.

The same balancing principle was applied to the engineered solutions developed. For sites where the size of potential future failures and the available space within the road reserve allowed, like at the Runaway rock slide, simple measures such a catch ditch at the toe of the slope were preferred. Comparatively, for the larger failures where control measures cannot be practically built, such as at Twin Faces rock slide, near-real time slope monitoring systems were implemented.

4 CONCLUSIONS

Different types of landslide occur in the Eastern Bay of Plenty, with landslide type strongly influenced by local geological and geomorphological conditions. The largest landslides tend to occur in the greywacke hills of the Waioeka Gorge, impacting SH2 on a regular basis, although large failures have also occurred elsewhere. Rainfall is the main triggering factor, with large failures often associated with rain events of around ARI=2 years (both for 24h rainfall and/or longer periods).

An understanding of landslide typology, as well as of the road environment impacted by the landslides, is fundamental to the development of practical risk management strategies. Staged risk management strategies, which were often influenced by movement reactivations, included visual and survey monitoring, reactive and/or pre-emptive controlled operation of highway operation, and temporary or long-term engineered solutions.

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