

Landslide Damage to Road Networks in the 2021 Marlborough Storm

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ABSTRACT

A large storm occurred in Marlborough in July 2021, causing widespread damage and severe disruption to the Marlborough Sounds road network from landslides, flooding, scour, and failure of retaining walls. Comparison of rainfall gauge data and historical records indicate that the average recurrence interval (ARI) of the storm was between a 15 and 40-year event, though hourly rainfall intensities may have had higher ARIs. Poor drainage and early road construction practices contributed to the damage, and the impacts were exacerbated by the narrow road corridors and lack of alternative routes. Initial rapid route assessment was carried out in the week after the storm to triage landslide damage and over 1500 network faults were recorded. Of these, 165 significant geohazard sites were added to a monitoring regime across three key roads in the Marlborough Sounds. The observed landslide mechanisms included debris flows, deep rotational slides, shallow planar slides, and rock falls. Evacuation of historic side-cast fill deposits was frequently observed, and scour and backfill loss was the primary cause of retaining wall failure. Subsequent weekly and post-rainfall inspections of the worst-affected roads have been carried out from October 2021 to March 2022. This paper presents a categorisation of the observed failures and observations on the ongoing behaviour of slip-damaged sites.

Keywords: Landslide; Rainfall; Road networks; Retaining Walls; Marlborough

1 INTRODUCTION

Transportation routes are critical lifelines for the community, particularly in the event of natural hazards. New Zealand has rugged terrain, which means that engineered cut and fill slopes are required to form transportation routes. In 2021 a heavy rainfall event occurred between the 16th and 19th July, affecting the upper South Island. The flooding and landslides that resulted caused severe damage to road networks, including key roads in the Marlborough Sounds (“the Sounds”) region. The recovery effort to restore the road network is the second largest post-disaster recovery for a local road network, after the Christchurch earthquake damage (Marlborough District Council, 2022).

Understanding the mechanisms and distribution of failures, and relating these to the impacts on infrastructure, is important for emergency response planning and for implementing measures to enhance the resilience of the roads. This storm provides a valuable opportunity to document slope failures along the road corridors and their consequent effects on the network. This paper provides a summary of the landslide damage observed on these key roads in the Sounds, and the impact this damage had on the road network in the year since the event. Data capture and analysis of landslide damage occurring from mid-July 2022 onwards has not been incorporated into this paper.

2 SETTING

2.1 Geology and Geomorphology

The Sounds are located in the upper South Island and are characterised by submerged valleys and steep surrounding topography. The bedrock of the Sounds is mapped as undifferentiated Caples terrane TZII schist. The schist generally has a deep and intense weathering profile, with completely weathered rock breaking down to a soil which displays clay-like properties. Strongly foliated schist is commonly found at depths greater than two metres deep and ranges from extremely weak to strong. The schist is jointed, with occasional crushed zones and clay-infilled seams. Large areas of the Sounds are also mapped as undifferentiated Pleistocene – Holocene landslide deposits ranging from coherent shattered masses of rock to unsorted fragments in a fine-grained matrix (GNS Science, 2013).

2.2 Historical Development and Road Formation

The majority of land in the Sounds is sloped at greater than 25°, with significant areas in the western end of the Sounds of very steep slopes (>35°) (Wolter, et al., 2022). Given the steep, topography and

remote location, road networks were originally developed for farming and forestry purposes with a standard width of 4m and grades of less than 8H:1V (Miller, 2015). This involved significant construction of sidling fills, with anecdotal evidence for an unengineered construction methodology involving cutting of the slopes on the uphill side of the road and side-casting this material over the pre-existing slopes on the downhill side. As the population has grown in Marlborough and the use of the Sounds for residential and recreational purposes has increased, the roads have been widened and sealed to accommodate the additional traffic. Records on MobileRoads (2022) suggest that much of QCD and Kenepuru Road (to Portage) were sealed in the 1970s.

3 JULY 2021 STORM EVENT

3.1 Rainfall

The storm event occurred over the weekend of 17 to 19 July 2021. Marlborough District Council (MDC) collects and records rainfall data in 24 hour increments across a number of rainfall gauges in the Sounds (Marlborough District Council, 2022). Data from the most relevant rainfall gauges is presented in Table 1. These gauges are located at Kenepuru Heads (intersection of Kenepuru and Titirangi roads) and south of Havelock on the Kaituna River.

Table 1: HIRDS v4 Rainfall for Kenepuru Head and Kaituna (source: (NIWA, 2017))

Rainfall Gauge	24 hr max rainfall	HIRDS ARI ^a	48 hr max rainfall	HIRDS ARI ^a
Kenepuru Head	196 mm	15 years	271 mm	30 years
Kaituna @ Higgins Bridge	154 mm	15 years	229 mm	40 years

^a Average Recurrence Interval

Analysis of Metservice rain radar data by GNS Science indicated that there were large areas across the Sounds that received high intensity (>25mm/hr) and large overall depths of rainfall (>400mm) that were not well captured by the MDC rain gauge network (Wolter, et al., 2022). Based on their analysis, GNS reports that the storm in the Kenepuru Head area had an ARI of ~100 years over 48 hours. Localised areas of high intensity rainfall are expected to have occurred around the centre of Kenepuru Sound.

3.2 Road closures

The storm event caused over 1,500 faults on the road network, including landslides, rock falls, debris flows, flooding, scour, underslips, tree falls and damage to retaining walls and bridges. Kenepuru Road, Queen Charlotte Drive (QCD) and Moetapu Bay Road (MBR) were all closed to traffic immediately following the storm due to overslip debris. Work to reopen the roads proceeded straight away, with different levels of prioritisation for each road based on their One Network Road Classification (ONRC)(Waka Kotahi NZ Transport Agency, 2022). At the time of writing (July 2022) ongoing recovery works mean that Kenepuru Road and MBR are still subject to frequent day-time closures. Works on QCD are typically within one-lane closures. The locations of failures on this part of the Sounds network are shown in *Figure 1*.

Queen Charlotte Drive (QCD)

Overslips were cleared quickly on QCD, allowing access for residents within 4 days, with the exception of a debris flow and underslip site near Havelock which remained closed for all traffic for 2 months. While access along QCD was possible, there was still significant debris and silt on the road surface, with water overtopping the road in several locations due to culvert blockage. Overslip clearance to reinstate two lanes was prioritised on this road and took place throughout August and September 2021.

Kenepuru Road

On Kenepuru Road, single lane access past overslips was also quickly reinstated, however the available corridor tended to be narrower and ongoing movement of overslip debris meant that many sites were initially only passable for 4WD or high clearance vehicles. A significant rockfall at RP19.660 (nicknamed "The Rock") blocked the road completely until November, which meant there was boat access only for residents of the outer Sounds. Underslips along Kenepuru Road also restricted access; heavy vehicles could not traverse past narrow underslip sites at RP12.8 and RP28.50, and significant deformation of the road surface due to 'global' slope deformations also required a 4WD vehicle in several locations.

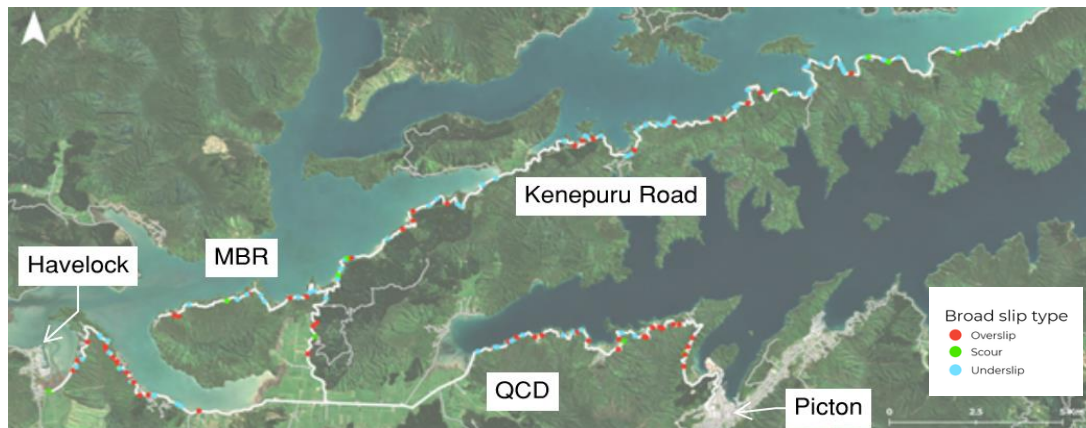


Figure 1. Locations of slope failures on the road network

Over the 12 months following the storm, there was also more notable deterioration of sites along Kenepuru Road resulting in closures being introduced at RP19.6 (Mistletoe Bay underslip) and RP20.5 (Watertank underslip). As Kenepuru Road provides the sole vehicle access to the outer Sounds, road retreat into the hillside around the more significant underslips was prioritised.

Moetapu Bay Road (MBR)

Access along MBR was restricted by underslips at RP0.5 and RP3.0 as well as by several significant debris flows and overslips. The two major underslips limited access for heavy vehicles until a road retreat could be carried out, which in turn prevented the clearance of the debris flows and overslips. Single lane access was open for vehicles within a week after the event, and debris clearance from the overslips began in February 2022, following earthworks to retreat the road at RP0.5 and RP3.0.

Table 2: Timeframes for road reopening from storm event (17th July – including weekends)^a

	Controlled resident access restored	Public access restored
QCD (Picton - Linkwater)	4 days	42 days (28 th August 2021)
QCD (Linkwater - Havelock)	60 days	61 days (20 th September 2021)
Kenepuru Road	4 months, 13 days	~ 8 months (11 th March 2022)
Moetapu Bay Road	10 days	~ 12 months (7 th July 2022)

^a Some dates are based on the timing of regular road inspections, therefore may not exactly reflect when the road status changed.

4 SLOPE FAILURE MECHANISMS

4.1 Overslips

Overslips range from small slumps and rock falls to large volume landslides on the hillslopes above the roads. Overslips were the principal cause of the immediate road closures in the Sounds, but single-lane access was typically reinstated within 2 to 7 days, with priority given to reopening QCD as a Primary Collector Route (the highest category route for the Sounds). The key characteristics of overslips observed in the Sounds are described below.

4.1.1 Debris and mud flows

Debris and mud flows occurred in high steep catchments, most frequently on the western end of QCD (Mahakipawa hill) and along Kenepuru Road (Figure 2A). Flows occurred in both clear-felled, mature forestry and native bush catchments. The liquefied flow material frequently blocked culverts and redirected surface water where they crossed the road corridor, consequently triggering underslips and scour damage below the road. Large volumes and high saturation of the debris resulting from flow failures meant these sites took longer to clear than any other form of overslip.

4.1.2 Rock fall

Rock falls were common from steep cut slopes formed in the weathered schist bedrock throughout the Sounds. These failures tended to have a minor impact on the road network overall as they resulted in smaller volumes of debris and often only extended partially into the road lane (Figure 2B). One significant exception to this was 'the Rock' site, where a car-sized boulder toppled and blocked the road (Figure 2D). Clearing the boulder took several weeks, however this site was part of an extended unstable slope and was closed to all traffic till November while additional earthworks were carried out.

4.1.3 Undifferentiated slides

There were a variety of mechanisms seen in sliding failures of overslips above the road. Some examples include planar slides along soil-rock interfaces and along dipping foliation planes, rotational slumps in over-steep cut slopes and compound slides in rock slopes (Figure 2C). Slides on high hillslopes would often transition into debris and mud flows by the time they intersected the road corridor. The impact of overslips typically depended on their size and location, rather than failure mechanism.

Small to medium volume overslips occurring from steeper natural slopes and cut batters were fast to clear but often failed again, depositing small quantities of debris on the roadside regularly after rainfall. Larger failures in locations with thicker soil deposits and deeper weathering profiles often required more extensive initial earthworks as the slopes would regressively fail as the slip debris was removed from the toe. Benching slopes was an effective way of reducing the quantity of debris that reached the road, though benches would often 'fill up' with debris and lose their effectiveness over time (Figure 2E).

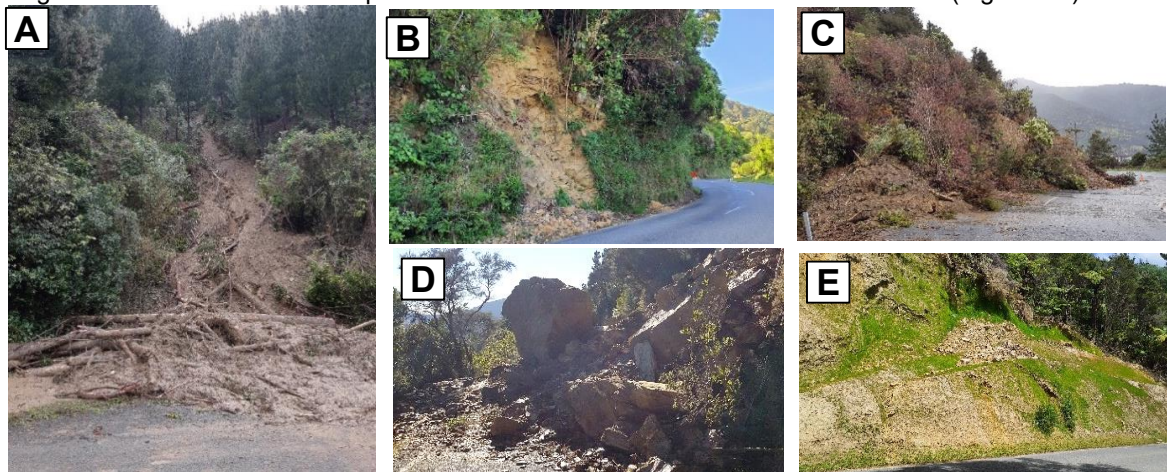


Figure 2. Typical examples of overslips. (A) Debris flow. (B) Small rock fall from a cut in weathered schist. (C) Undifferentiated slide (D) Large rock fall at The Rock (E) Ongoing failure of benched slope.

4.2 Underslip Failures

Landslides below the road caused the most significant outage, due to their greater complexity to fix than overslips. At the time of writing, 26 single lane closures due to underslips remain in place. The characteristics of underslip failures are described below, and examples are shown in Figure 3.

4.2.1 Shallow planar slides

Shallow planar slides typically occurred on slopes $>30^\circ$ and involved the surficial layers of colluvium and residual soil with an estimated depth of $<1\text{-}2\text{m}$ (Figure 3A). The debris from these slides frequently developed into flows, often extending down to sea level. These types of failures typically occurred in road shoulders and showed minimal signs of regression after the initial event, though the exposed soil was vulnerable to scour.

4.2.2 Side-cast fill failures

Typically developing as planar slides, side-cast fill failures occur in the outer road lane, often developing initially as cracking and subsidence at the edge of seal where water runoff saturates the soil. Side-cast fill failures can be difficult to differentiate from planar slides occurring on natural slopes, as the resulting damage is similar, however, these slips tend to extend further into the road corridor resulting in greater impact on the road network. In 12 months, 3 sites that initially consisted of cracking and subsidence of the road edge developed into fully evacuative failures (Figure 3B). The evacuation occurred rapidly following rainfall, with no notable deterioration of the site pre-rainfall which would have predicted the failure.

4.2.3 Rotational slides

Rotational soil slides are characterised by semi-circular head scarps that have developed in the shoulder or road lane. Most of these slips tend not to have not fully evacuated, with the bulk of the slip mass is still in place with a steep semi-circular head scarp. Where the slip extended into the road, they tend to remain un-remediated 12 months after the storm with single lane closures still common, particularly on Kenepuru Road. Regular inspections showed that the slip masses settled and cracks widened in the

first few months following the July storm, however, over summer the displacement ceased. At the sites that did evacuate (Figure 3C) the deep slip surface resulted in steep slip scarps greater than 3 m which limited heavy vehicle movement on the narrow road for over 6 months.

4.3 Retaining Wall Damage

In general, retaining walls performed well during the July storm event. The observed damage to the most common wall types is described below.

4.3.1 Driven rail-iron retaining walls

The most common form of retaining wall in the Sounds, rail-iron walls are formed from driven rail iron piles with timber lagging. They have a typical height of 1.5-3.5m and are frequently tied-back to a deadman pile below the road. Where tie-backs were present, these walls typically performed well during the storm. The primary form of damage was the formation of large voids behind the timber lagging. This was initially attributed to scour, however following inspection it was found that voids were forming below the base of the timber lagging due to underslips in front of the wall (Figure 3D & 3E). These voids allowed the loose backfill to migrate out from behind the wall. At several retaining walls, the geotextile wrapped around the base of the backfill was the only thing preventing further creation of voids behind the wall.



Figure 3. Typical examples of underslips and wall failures. (A) Planar soil slide. (B) Side-cast fill failure into a planar slide. (C) Rotational slide at MBR RP3.0. (D) Void behind rail iron retaining wall. (E) Loss of backfill below lagging. (F) Global slope deformation.

4.3.2 Gabion retaining walls

Gabion walls in use in the Sounds tend to be 1-2 m high and used for widening of the road shoulder and around culvert outlets. It is anticipated that they were frequently installed on poor foundations of side-cast fill or soft soil. Undermining and collapse of gabion walls was noted in 5 locations. The loss of the wall was typically accompanied by a shallow, planar slide on the steep slope below the road. Tie-backs were observed inconsistently at different failures. Less common forms of failure noted included cracking in the seal due to settlement and overturning of the entire wall due to bearing failure. Several large, well-engineered gabion walls (>3 m) are present in the network and showed no sign of damage following the event.

4.4 Slope Deformation

Deformation related to large, deep-seated movements of hillsides encompassing the whole road bench were noted in 11 locations after July 2021. Common damage observed was transverse cracking across the road, with large vertical distortion in the pavement, indicating a slip surface which passed below the road (Figure 3F). Often these slips were accompanied by smaller overslips or underslip / toe failures, while culvert disjuncting and tomo-formation was also common. None of these slips were seen to have fully evacuated, and the slope deformation consisted of limited displacement of the landslide mass. These movements were traversable by 4WD vehicles immediately after the storm, and due to the scale they are typically managed by re-leveling and monitoring the road. These slope deformation features were typically located in areas mapped by GNS as Pleistocene-Holocene landslide deposits. The movements are expected to reflect re-activation of lobes of large relict landslides, occurring due to elevated ground water after prolonged rainfall.

4.5 Scour Damage and Culvert Failure

The context of local road networks in the Sounds (as low volume roads surrounded by steep, heavily vegetated slopes) result in stormwater infrastructure which is often undersized and difficult to maintain. Culvert failure was generally a result of corrosion of corrugated iron culverts or disconnection of butt-jointed concrete culverts. Failure resulted in backfill loss behind retaining walls, piping erosion and formation of 'tomos', and sometimes contributed to the development of larger failures. Without remediation, scour and underslips that resulted from culvert failures tended to worsen over the monitoring period. Scour damage unrelated to culverts was less common. It tended to result where a debris flow or large overslip had blocked and diverted existing water courses into roadside channels, resulting in much larger water volumes than would usually be experienced.

5 OBSERVATIONS FROM ONGOING MONITORING

Visual monitoring of landslides was carried from October 2021 to July 2022, which allowed deterioration or head scarp regression to be monitored over an extended period. It was observed that over half of the monitored landslides deteriorated to some degree within the 9 months, and with the most significant deterioration of the landslides occurring in the initial 3 months following the storm event while the soils were still saturated.

The overslips tended to be the most active of the slips monitored, with approximately 66% showing instability over the year to July 2022. This is likely due to the easy recognition of activity from these slips (i.e. failed material on the road or table drains). In contrast, just under half of the underslips worsened. This was largely noted as minor regression of the scarp, minor settlement of the road edge, or an increase in cracking within the seal. Ongoing failure of overslip sites was more common on slopes with more highly weathered rock and thicker overlying soil deposits. These sites were reprofiled with benches to catch debris, and while there were ongoing failures of the upper batter slopes these had minimal impact on the road as the debris collected on the benches.

6 CONCLUSIONS

The damage caused by the landslides across the Marlborough Sounds provided valuable lessons on the impact of road performance in a remote setting. Damage to the network was widely spread across the three key roads within the Sounds. Overslips were the most widely distributed but tended to be easiest to clear, while underslips have resulted in the longest outages, with single lane sections still remaining on all key roads at the time of writing. Underslips required considerable time to proceed through to construction; requiring stages for options assessment, investigation, design, tendering and procurement all before construction could commence. The overall scale of the damage distributed across a highly constrained road network through steep and unstable terrain meant that significant landside damage remains un-remediated 12 months following the storm.

Regular monitoring and post-rainfall inspections provided insight into how the landslide sites deteriorated over time. Overall, the monitoring showed that very few sites worsened significantly during the monitoring period. Ongoing damage generally consisted of minor regression of slip scarps or small overslips. Exceptions to this were several notable rapid failures of underslips, which were originally expressed as minor cracking in the outer road lane in the July 2021 event, and regressive failures of large overslip sites which required more significant earthworks and benching to reduce the road impact.

This paper was written at the beginning of July 2022 to record the status of the road network in the 12 months following the July 2021 storm. Since writing, Blenheim has been reported as experiencing its wettest month on record in July (Stuff, 2022) and then suffered a larger storm event on August 17th-18th. There has been significant damage to the road network in the Sounds and quantifying the impact of these storm events on the network will take some time.

7 ACKNOWLEDGEMENTS

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