NZGS SYMPOSIUM 2021
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24-26 March 2021 • Dunedin • New Zealand

Jacobs Ladder – A Case-History of Debris Flow in a Post-Seismic Environment

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ABSTRACT

An increase in debris flows, and other slope stability events, over the short to medium term following significant seismic events is well recorded in international literature. The 2018 Jacob's Ladder debris flow, initiated as a result of the 2016 Kaikōura Earthquake, offers a practical example of this within a New Zealand context.

Shallow translational landsliding occurred on the side slopes of the Jacobs Ladder catchment as a result of the earthquake, adding to a historical debris load in the gully. Cyclone Debbie, in early April 2017, triggered an approximately 10,000 m^3 debris flow which originated in the lower part of the catchment. The February 2018 Cyclone Gita rainfall event triggered a much larger debris flow, involving a total volume of around 90,000 m^3. The coastal transport corridor was severely disrupted following the Cyclone Gita event with the State Highway remaining closed for 10 days and the Main North rail line closed for 15 days.

The potential for debris flow initiation was recognised in 2017 as part of evaluation of the resilience of the transport corridor following the Kaikōura Earthquake. Engineering geological assessment included observations of the failures that occurred to date from Jacobs Ladder catchment, LiDAR DEM difference modelling and an estimation of the potential for inundation of the transport corridor from future debris flows. Engineering works, designed to mitigate against a reasonable worst-case future debris flow, have involved construction of a large receiving basin upslope of the transport corridor and a flow conveyance structure underneath the corridor.

1 BACKGROUND

Large earthquakes not only trigger severe landslides but also increase the number and intensity of subsequent rainfall-induced landslides, including debris flows. Experience from the 1999 Chi-Chi earthquake in Taiwan and the 2008 Wenchuan earthquake in China show that the critical rainfall thresholds for triggering landslides and debris flows decrease significantly following large earthquakes, commonly reducing to between 25% and 75% of the pre-earthquake threshold (e.g. Guo et al., 2016; Lin et al., 2003). This persists for over a period of approximately 5-6 years, with a gradual return to the pre-earthquake conditions (eg Hovius et al., 2011). In mountainous terrain, the period of increased susceptibility can take significantly longer (greater than 12 years; Li et al., 2016; Tang et al., 2016).

Jacob's Ladder provides one example of this post-earthquake susceptibility in a New Zealand context. Significant co-seismic slope instability occurred in the Jacobs Ladder A catchment (refer Section 1.1 below) as a result of the M_w 7.8 November 2016 Kaikōura Earthquake. A very large debris flow was subsequently released during the approximately 1 in 30 to 1 in 50 year return period event in Cyclone Gita in February 2018. However, Jacobs Ladder A did not appear to release a significant debris flow following the much larger Cyclone Allison event in 1975, nor in other large rainfall events prior to the Kaikōura Earthquake. Furthermore, the catchment was not recognised as being a significant debris flow hazard prior to the earthquake.

1.1 Location

The Jacobs Ladder catchments are located approximately 24 km northeast of Kaikōura on New Zealand's South Island (Figure 1). The Jacobs Ladder A catchment area comprises two southeast-trending gullies (termed the northern and southern gullies, refer Figure 1) which originate below a ridge approximately 660 m above sea level (masl). The gullies converge at approximately 300 masl forming a single gully which trends southeast to the apex of the depositional fan approximately 40 m to 50 masl.

The Jacobs Ladder B catchment comprises a somewhat smaller catchment located immediately to the north. Bell (1975) records that a significant debris occurred from this catchment following Cyclone Allison, which produced rainfall exceeding a 1 in 200-year return period across a large portion of the Kaikōura Coast. The Jacob's Ladder B gully has to date been much less active compared to Jacob's A, and has not been discussed in detail in this paper.

The transport corridor comprising State Highway 1 (SH1) and the Main North rail Line (MNL) are located at the narrow coastal plain, as shown on Figure 1.

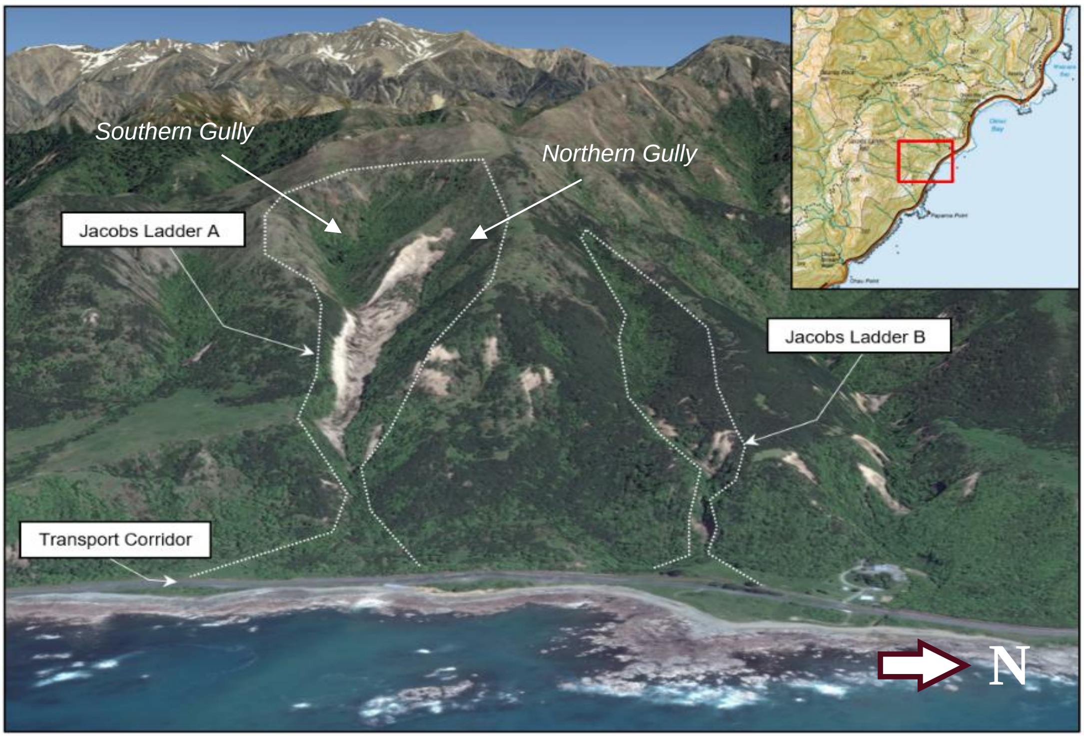

Figure 1: Jacobs Ladder Debris Flows Catchments. Image sourced from Google Earth. Image dated May 2019

1.2 Geological Setting

As described in Justice et al (2018), basement ‘Greywacke’ of the Pahau Terrane forms the hills along the coast south of Kaikōura and much of the North Kaikōura Coast, including the area of the Jacobs Ladder catchments. The Greywacke typically comprises slightly weathered sandstone and mudstone (argillite), often with a mantle of moderately weathered rock close to the ground surface. The mudstone is typically weak while the sandstone is moderately strong to strong.

Colluvium overlying the Greywacke is typically a mixture of rock fragments, silt and sand. It is widely distributed over the basement rock throughout the project area, where slope angles are less than 45°. The colluvial mantle is typically 0.5 m to 1 m thick near the ridge tops, and increases in thickness downslope, with a maximum observed thickness of approximately 15 m.

1.3 Topography

The Jacobs Ladder A catchment has an area of approximately 0.345 km^2. The slopes on the sides of the upper catchment area are typically between 35° and 60° with the south-western side of the northern gully being the steepest. The gully floor is estimated to have a stream gradient of around 23° (42%), however the slope angle locally varies significantly. The lower gully cuts through and erodes an elevated pre-historic alluvial fan, before spreading out onto the modern-day debris fan where the flow leaves the gully confinement. Prior to debris flow mitigation works, the surface of the fan sloped at approximately 10° to 15°.

Aerial images prior to the November 2016 earthquake show the gully was well vegetated with no obvious signs of recent slope failure (Figure 2), however a fairly well developed depositional fan at the base of the gully indicates a history of debris transport and deposition (historic debris flows, debris floods or lower energy erosion and deposition).

1.4 November 2016 Earthquake-induced Landsliding

A large evacuative landslide with a plan area of approximately 30,000 m^2 occurred on the northern gully of the Jacobs Ladder A catchment as an immediate effect of the November 2016 earthquake, as can be observed in the aerial photograph taken in December 2016 (Figure 2). Seismically induced slope failure also exposed a bedrock structure (interpreted to be a bedding plane or persistent defect) subparallel to the slope on the north-eastern side of the northern gully of the catchment.

Rock exposed on the southwest side of the northern gully also appears to have a pervasive defect plane dipping subparallel to the slope on the south-western side, possibly forming a large-scale wedge failure at the intersection in the base of the gully.

1.5 Debris Flows since the Kaikōura Earthquake

In early April 2017, ex-tropical Cyclone Debbie triggered an approximately 10,000 m^3 debris flow which initiated in the lower part of the gully, with the scarp just upslope of a slight curve in the gully at approximately 170 masl. This part of the gully appears to incise through pre-historic alluvial fan gravel on the south side of the source area but is below the toe of the large earthquake induced landslide outlined in Section 1.4. The majority of the debris flow appeared to have been deposited in the lower part of the confined gully, above the fan apex (Figures 2 and 3), however the MNL was inundated with bouldery debris and SH1 with water and some silt. Rainfall during the Cyclone Debbie event appears to have had a return period somewhat less than 1 in 5 years.

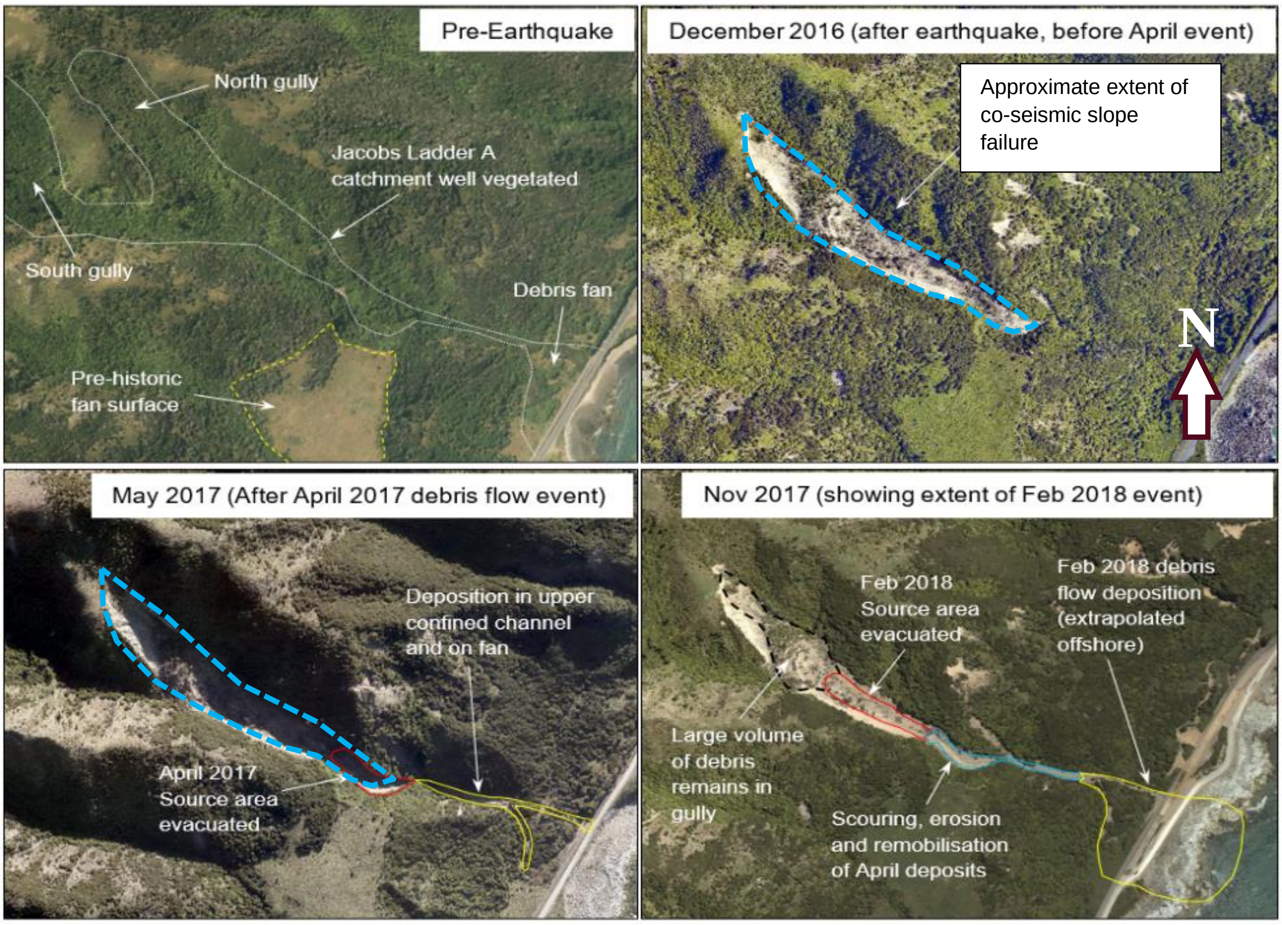

Figure 2: Jacobs Ladder A aerial photographs showing changes since the November 2016 earthquake

Rainfall events in mid-April (ex-Cyclone Cook), June, August and October 2017, as well as January 2018 do not appear to have triggered significant debris flows, however, these events had return periods typically less than 1 in 5 years. Having said this, some deposition may have gone unnoticed on the south flow path of the debris fan.

In February 2018, ex-tropical Cyclone Gita rainfall triggered another debris flow initiating in the gully upslope of the April 2017 source area near the confluence of the north and south gullies. The debris flow deeply scoured the toe of the earthquake induced landslide described in Section 1.4 and remobilised much of the deposit from the April 2017 event that had lodged in the lower confined channel and on the upper fan (Figures 2 and 3). The rainfall during Cyclone Gita has an annualised return period of 1 in 30 to 1 in 50 years for a 24-hour duration event in the area surrounding the Jacobs Ladder catchments.

Approximately 90,000 m^3 of debris was deposited on the exiting fan during the Gita event, extending beyond the shoreline and inundating the transport corridor. The coastal transport corridor was severely disrupted following Cyclone Gita with the State Highway remaining closed for 10 days and the Main North rail line closed for 15 days. The volume of debris removed to clear the road and rail was approximately 18,000 m^3 with deposited material ranging from silt and fine sand to boulders greater than 1 m diameter.

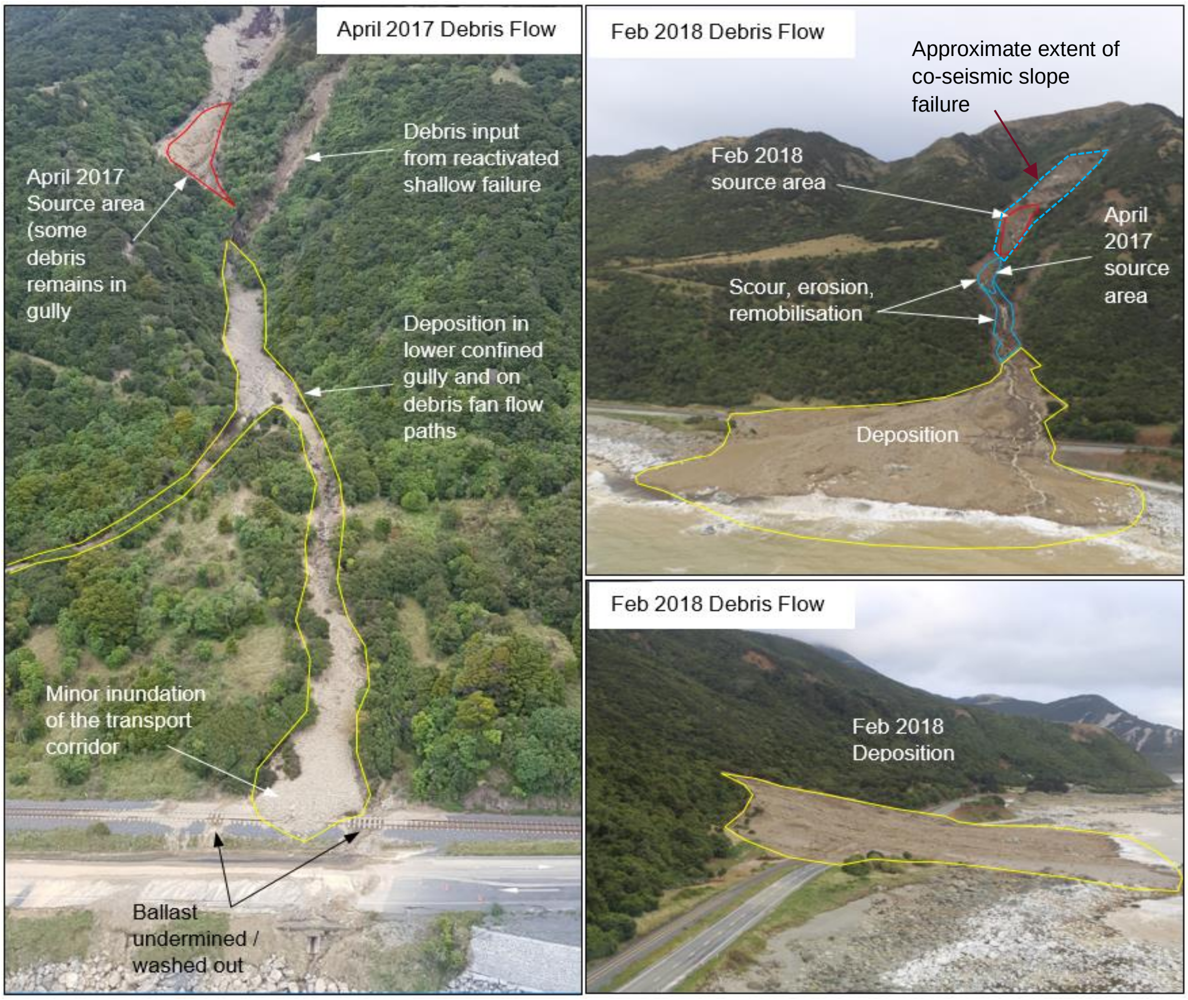

Figure 3: Jacobs Ladder A debris flows – April 2017 (left) and February 2018 (right)

2 LIDAR DIFFERENCING

Four sets of LiDAR imagery have been flown since the November 2016 earthquake: November 2016, May 2017, November 2017, and June 2018.

Elevation differencing between the November 2016 - May 2017 and May 2017 – June 2018 LiDAR datasets allowed for visualisation of changes in ground surface over key periods since the Kaikoura Earthquake. The LiDAR change maps indicate surface elevation change as a result of loss of material by erosion or evacuative landsliding or gain of material from deposition.

The first LiDAR difference map (Figure 4) indicates elevation change from November 2016 to May 2017 and covers the period of time in which the April 2017 Cyclone Debbie debris flow event occurred. The difference model shows the evacuation of debris from the source area in the gully bend with significant material deposition in the confined channel above the fan apex. To a lesser degree the two relatively small flow paths on the debris fan are also apparent, extending to the transport corridor. The change map shows little difference in the upper part of the gully – upslope from the 2017 debris flow source area.

The second LiDAR difference map (Figure 5) indicates elevation change from November 2017 to June 2018 and encompasses the debris flow event as a result of Cyclone Gita in February 2018. In contrast to the April 2017 debris flow event, the difference model indicates significant evacuation of material in the lower and central parts of the Jacobs Ladder A catchment, including total remobilisation of material deposited above the fan apex during the earlier event. The upper part of the erosion zone of the Gita event appears to be within the toe of the large earthquake induced landslide in the northern gully of the catchment, as outlined in Figures 2 and 3. Deposited material from the debris flow event can be clearly seen extending across most of the width of the modern debris flow fan and lengthwise to the Pacific Ocean. The area of inundation of the fan is measured at approximately 46,000m^2, and with an assumed average depth of deposition of 2m based on the LiDAR differencing map, a volume of over 90,000 m^3 is apparent (Table 1). This relationship between area of inundation and volume appears to be broadly consistent with that outlined in Jakob (2005).

Table 1: Summary of Debris Flow Events.

Debris Flow Event	Approximate ARI	Crest of Erosional Zone	Erosion Area	Deposition Area	Estimated Debris Flow Volume
April 2017	< 1 in 5yrs	170 masl	2560 m^2	2530 m^2	10000 m^3
February 2018	1 in 30 to 50yrs	275 masl	14900 m^2	46000 m^2	90000 m^3

Note. Areas indicated are in plan, as measured from LiDAR difference models (Figures 4 and 5). ARI – Annual Recurrence Interval

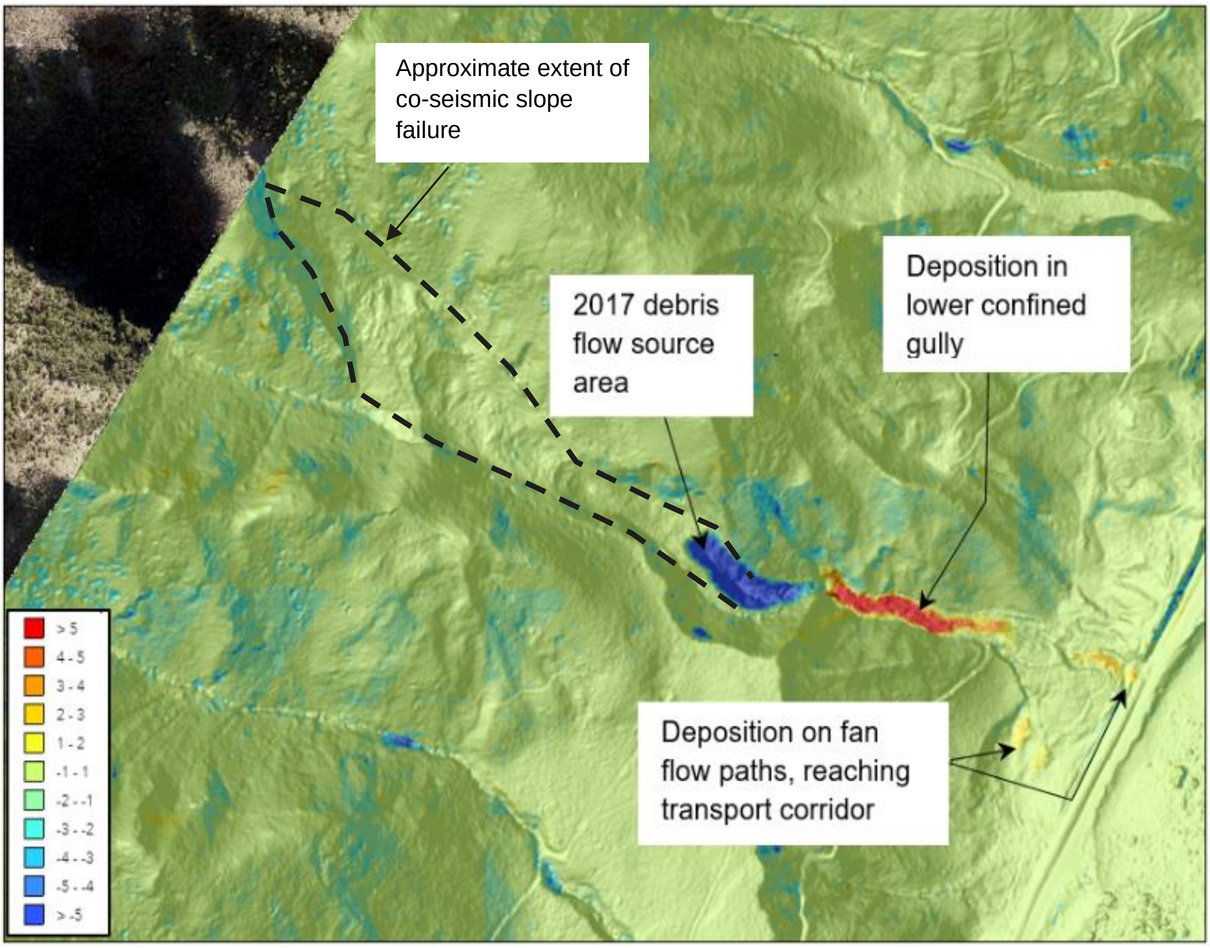

Figure 4: Jacobs Ladder A LiDAR change model showing surface elevation change from November 2016 – May 2017 (elevation change scale is in metres but should be seen as indicative only)

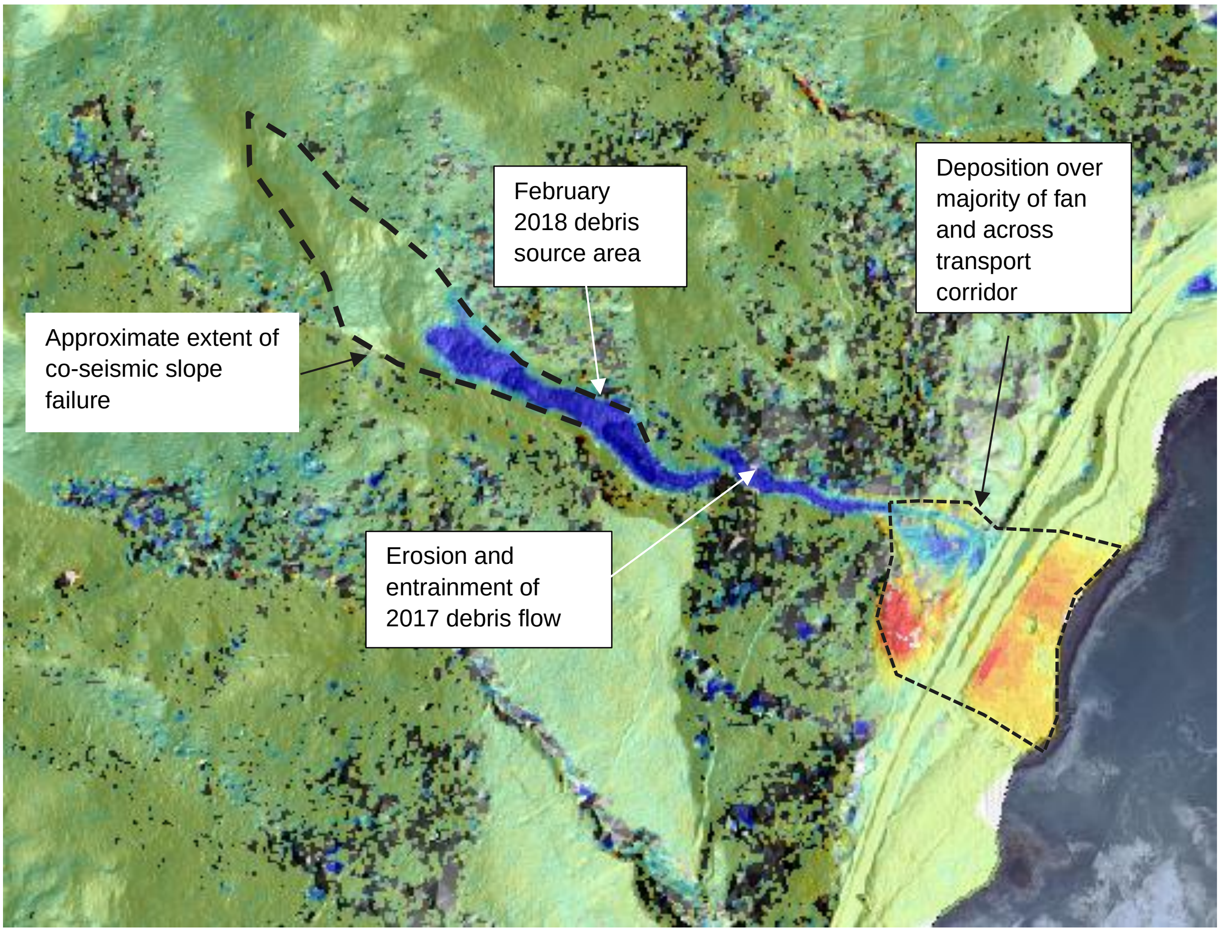

Figure 5: Jacobs Ladder A LiDAR change model showing surface elevation change from November 2017 – June 2018 (scale as indicated in Figure 4). Poorer survey resolution in the later survey is represented by the areas of missing data.

3 INTERPRETED FUTURE HAZARD AND MITIGATION

A much larger debris flow volume was released from Jacobs Ladder A following Cyclone Gita than what the catchment area would be expected to release based on empirical data (see for example, Van Dine, 1996, D'Agnostino & Marchi, 2001; which would suggest debris flow volumes between 30,000 m^3 and 38,000m^3). This is attributed to a combination of:

- Preconditioning of the upper part of the catchment as a result of co-seismic landsliding in the northern gully
- Entrainment of a significant volume of material accumulated in lower portion of the confined gully that was deposited in the previous debris flow event in April 2017.

Based on the site observations and the performance of the Jacobs Ladder A catchment during Cyclones Debbie and Gita as well as during lesser rainfall events, the following pattern of behaviour was considered:

- The catchment does not appear to generate significant debris flows during low to moderate intensity rainfall events however it does appear that following the April 2017 debris flow there was still some debris in the source area which had moved by the May 2017 LiDAR survey. Additional debris flows may have gone unnoticed, with deposition possibly occurring above the fan apex or in the flow path that curved south away from the corridor. The gully response to rainfall may have changed since the Cyclone Gita event due to scouring in the lower catchment and possible changes to the stability of the debris load in the upper catchment.

- It is possible that the coarse nature of the debris in the gully allows water to drain relatively easily during frequent (i.e. smaller) rainfall events. Some surface erosion is evident on debris load in the upper catchment, particularly since the February 2018 Cyclone Gita event, however it appears the material is generally relatively free draining near the surface.
- A significant volume of debris from the co-seismic landslide remains in the northern gully, immediately upslope of the February 2018 erosion area. Future remobilisation of this material under high intensity rainfall events is considered likely and is expected to produce very large debris flows for the size of the catchment. Side slope failure around the oversteepened channel is also expected, which is likely to introduce material into the floor of the catchment that could subsequently be incorporated into a debris flow under moderate rainfall events.

For design purposes, future geotechnical hazards were anticipated to include:

- Mobilisation of relatively small debris flows (less than approximately 25,000 m^3) under rainfall events with approximately a 1 in 5-year return period.
- Initiation of relatively large debris flows (volumes of between 50,000 and 100,000 m^3) under storm events greater than approximately 1 in 25 years.
- Landsliding in the catchment, potentially leading to damming the gully with subsequent failure and debris flow initiation under a relatively low intensity rainfall. Landslides are expected to most likely to be initiated under a moderate to large earthquake event (MM7 or greater).

3.1 Resilience Improvement Works

To improve resilience (refer Mason et al, 2018 for further details) of the transport corridor, the following mitigation works were constructed under the NCTIR program:

- Excavation of a large retention basin on the upslope side of the transport corridor, and;
- Placement of a large (4m square) culvert beneath road and rail. The dimensions of the culvert have resulted from Safety in Design considerations for maintenance works, to permit truck and excavator passage underneath the transport corridor, allowing debris flow material to be cleared with minimal disruption to road and rail traffic.

The overall intent of the improvement works is to allow gravel and boulders entrained within any future debris flow to settle out of suspension with the remaining material conveyed underneath the transport corridor to the coastal environment. The shape of the retention basin has been designed to:

- Allow low-flow water and clear flood waters expected during frequent (low annual recurrence interval) events to pass underneath the transport corridor with minimal impedance;
- Encourage deposition of coarser material expected within the debris flow (outlined below);
- Accommodate a theoretical debris volume of approximately 45,000 m^3, although the actual volume of future large events that will be contained will depend on the particular characteristics of the debris flow.

Debris flow deposition within the catch basin has been encouraged by:

1. Excavating the base of the catch basin to a floor slope of 1V:6H (approximately 9.5°). The grade of the catch basin is flatter than the slope angle on which debris flow deposition occurred at Jacob’s Ladder A as a result of Cyclone Gita (measured at approximately 14°). Additionally, Van Dine (1996) and Osanai et al (2010) indicate debris flow deposition will typically occur on slope angles between 2° and 15°.
2. Widening the existing debris channel to allow debris to spread out and lose confinement. Non-confined flows typically travel significantly less distance than a confined flow at the same gradient (Van Dine, 1996).

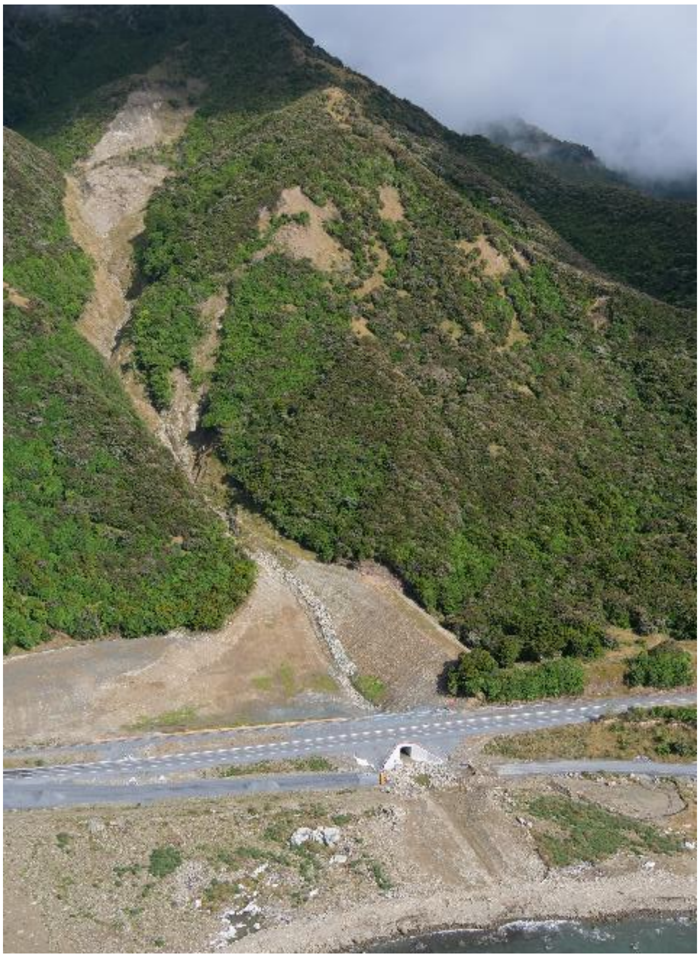

Figure 6: Completed resilience improvement works

4 CONCLUDING REMARKS

Between the Cyclone Gita event and the time of writing this paper, the Jacobs Ladder catchment had not been tested by any large return period rainfall events, and as such, the effectiveness of the mitigation works cannot currently be judged.

During the design of the Jacobs Ladder mitigation works (or any of the debris flow mitigation works designed on the NCTIR programme), little guidance was available with respect to a New Zealand context. The author suspects that previous design practices within New Zealand have largely been undertaken on an ad-hoc basis. Work is currently underway to provide a systematic guidance document for the assessment of debris flow hazards and design of suitable mitigation solutions.

5 ACKNOWLEDGEMENTS

The author wishes to acknowledge NZTA and KiwiRail as the owners of all assets discussed in this paper. All the works were designed and constructed by NCTIR and involved a team of designers, constructors and others. The work of Mr Mike Pretty to provide the engineering geological model for the debris flow is also gratefully acknowledged.

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