DEVELOPMENT OF AN EARLY WARNING SYSTEM FOR RAINFALL INDUCED SLOPE FAILURE AFFECTING RAILWAY IN A POST-EARTHQUAKE SETTING

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ABSTRACT

Following the 2016 M7.8 Kaikōura Earthquake approximately 30-40 large scale landslides inundated sections of the rail transport corridor. Onsite experience and international literature suggest earthquake damaged slopes are generally more susceptible to rain induced landslides, however the specific increased susceptibility for the Kaikōura area needed to be assessed. Moreover, rail operators needed to know what conditions were likely to result in slope failure and potential blockage of the track or impact to a train.

A record of slope failures that have occurred in Kaikōura since the earthquake was used to assess the susceptibility of the local slopes to rainfall induced failure. A correlation between total rainfall volume, assumed soil moisture and slope failure was established based on assessment of over 600 records of slope movement. Probabilistic thresholds were established based on the rainfall-slope failure relationship that was found for the Kaikōura area. Forecasting of expected rainfall volumes in relation to antecedent rainfall conditions enabled development of a predictive tool that is being used by rail operators to decide when to delay or cancel rail operations due to increased risk of slope instability.

1 INTRODUCTION

State Highway 1 (SH1) and the Main North Line (MNL) are significant transport routes for the lower South Island. The road and rail traverse the coastline to the north and south of Kaikōura township. The foothills of the (Seaward) Kaikōura Ranges extend to the coastline, meaning both transport routes are located on a narrow piece of land that skirts steep hillsides and sea cliffs.

The M7.8 Kaikōura earthquake of 14 November 2016 resulted in the closure of the coastal sections of both SH1 and the MNL, due to slope failures originating from above the road and rail corridor. Approximately 30-40 large scale landslides inundated sections of the transport corridor, with numerous other small scale landslides and rockfall.

The GNS Science 1:250,000 scale QMAP Sheet 13 (Rattenbury et al., 2006) describes the geology of the South Kaikōura Coast and in summary, the bedrock geology predominantly comprises interbedded Greywacke sandstone and siltstone. The Greywacke basement rock is overlain by varying thicknesses of colluvium over most of the area (typically comprising sands and gravels). The Greywacke is typically highly fractured and blocky, often with open jointing, and was significantly affected (loosened) by shaking associated with the Kaikōura earthquake. Recent (earthquake-induced) landslides are primarily shallow translational debris slides and rock wedge failures.

Extensive earthworks, repairs and construction of rockfall mitigation was required to enable the transport corridor to operate again. The North Canterbury Transport Infrastructure Recovery (NCTIR) was established in early 2017, as an alliance partnership between four large construction companies (Downer New Zealand, Fulton Hogan, HEB Construction and Higgins), the NZ Transport Agency (NZTA) and KiwiRail (the rail operator). The alliance brought together resources with the aim of effectively managing and completing the works required to enable safe operation of the transport network.

Since the establishment of NCTIR, several large rainfall events and numerous small rainfall evens have mobilised and re-mobilised slope material (in the form of landslides, rockfall and debris flow), often inundating parts of the road or rail. Management of the transport corridor requires a balance of safety and reliability, meaning operational responses to rainfall need to ensure life-safety whilst also considering reliability and minimising closure times as much as possible.

2 LITERATURE REVIEW

2.1 RAINFALL AS A DRIVER OF SLOPE FAILURE

For the purposes of understanding the response of slopes to rainfall in Kaikōura, two key considerations were investigated. The first consideration is of the “normal” slope behaviour and rainfall triggering response, and the second is consideration of the seismic effects.

2.1.1 Triggering Thresholds

Rainfall triggering thresholds for landslides have been developed by Crozier and Eyles (1980), Crozier (1999) and Glade et al. (2000) for the Wellington region (an area comprising similar greywacke terrain to that in the Kaikōura area). These studies use antecedent rainfall as an index of antecedent soil moisture and add daily rainfall input to soil water status (which is based on the rainfall over the preceding 10 days) to identify threshold conditions for landslide triggering (i.e. the amount of rainfall needed in the following day to equal or exceed triggering threshold). The probability that triggering rainfall will occur can then be determined from the frequency/magnitude distribution of the local rainfall record.

The rainfall triggering thresholds for Wellington are shown in Figure 1 (after Glade et al., 2000). The steepening slope of the threshold envelope for Wellington shows that continued wet antecedent conditions reduce the critical water content required for landslide initiation, and more water is required from antecedent rainfall than from rainfall on the day of slip occurrence. For example, using the 90% probability envelope, at zero antecedent conditions 140 mm of daily rainfall is required to exceed the threshold, whereas at zero rainfall 175 mm of antecedent rainfall is required to meet the same confidence interval.

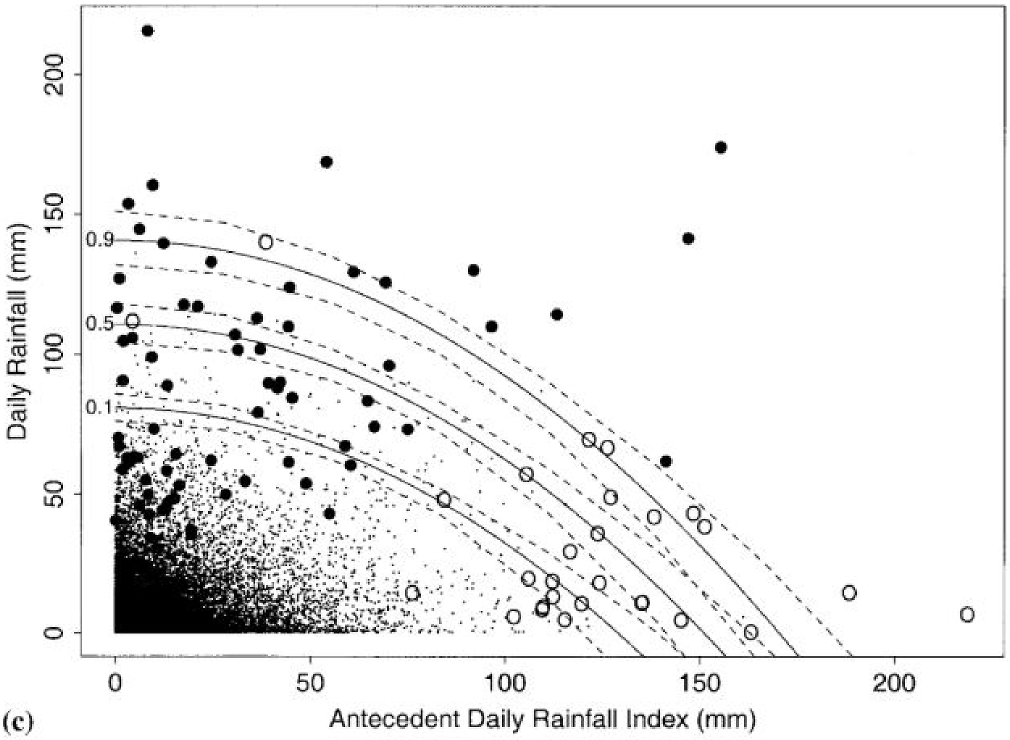

Figure 1: Rainfall probability thresholds for Wellington (Glade et al., 2000). Calculation is based on rain days (>0.1 mm) from 1862 to 1995. Large dots relate to rainfall which triggered landslides, open circles relate to rainfall with probable landslide occurrence, and small dots relate to rainfalls which did not trigger landslides. Confidence intervals are indicated for each probability curve by dashed lines.

2.1.2 Post-Earthquake Effects

Large earthquakes not only trigger severe landslides but also increase the number and intensity of subsequent rainfall-induced landslides (Lin et al., 2006; Zhang et al., 2014). 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; 2009; Zhou and Tang, 2014). Nomura et al. (2014) indicate that Japanese practice is to scale down the criterion for rainfall-induced landsliding by 20% to 50% to allow for seismic disturbance of slopes following a major earthquake

3 SITE EXPERIENCE

3.1 RECORDS OF SLOPE MOVEMENT

The scope of NCTIR construction works included a formalised process for recording and tracking slope movements to ensure safety of route traffic and construction staff. NCTIR have kept a record of natural slope instabilities that have occurred adjacent to the transport corridor since approximately March 2017 and the events under which these occurred. Records prior to March were not possible due to emergency "make safe" works, including active sluicing of most of the slip faces. Records of rainfall and on-going slope movement have been made during the sluicing, scaling and clearance of slips on the north and south coasts.

With the use of mobile technology, project-specific forms were used by geotechnical field staff to consistently record slope movements when and where they were observed. As of June 2018, NCTIR had recorded over 600 individual slope movement events, ranging from small scale rock fall to large debris slides and flows comprising several 100 m^3 of debris. Observations were generally made by geotechnical field staff via road patrols and helicopter flyovers. Telemetered monitoring fences were constructed at high risk locations, designed to alarm when impacted by debris. The records of debris impacts to monitoring fences provided an additional source of slope movement data. In summary, the NCTIR team's observations and data showed:

- Active landslide scarps were prone to further debris movement in very small rain events, proportional to antecedent soil moisture conditions and the amount and intensity of rainfall on the day of slope failure.
- The soil moisture condition had a strong influence on the amount of rain required to trigger further slope movement.
- Landslide debris fans were mobilised into channelised debris flows during moderate and unexceptional rain events and cause frequent problems to the transport corridor.
- Slopes that did not show obvious signs of failure or deformation in the earthquake have the potential to develop into large slope failures under moderate to large rainfall events.

3.2 WEATHER STATIONS

Telemetered automatic rain gauges were set-up along the affected sections of the MNL (attached to telemetered monitoring fences). The rain gauges were typically located close to areas prone to slope instability, providing relatively accurate information of the rain conditions associated with slope movements at those locations.

4 ESTABLISHING A MODEL FOR SLOPE FAILURE

4.1 END-USER REQUIREMENTS

The rail operator's requirement was for a simple and functional tool to help in the assessment of slope risks for safe operation of the rail, and to provide some certainty for freight customers. Decisions of when to close the rail due to significant rainfall needed to be made, and therefore a tool was needed to assess the hazard associated with rainfall events of varying scales.

4.2 DAILY RAINFALL VS ANTECEDENT RAINFALL INDEX MODEL

Given the significant time restraints on the NCTIR design team, a model that could be easily replicated was preferred (rather than development of an entirely new model). The model developed by Glade et al. (2000) was therefore chosen to be replicated, due to the geological similarities between Wellington and Kaikōura.

4.2.1 Daily Rainfall

To best characterise the rainfall conditions associated with each recorded slope failure, the corresponding rainfall data was gathered from the nearest rain gauge.

4.2.2 Antecedent Daily Rainfall Index

Remote sensing techniques and soil moisture probe sensors were considered for the collection of soil moisture data, however both options had a number of drawbacks. Remote sensing data was not considered to sufficiently represent the actual soil moisture on steep slopes and beneath thick vegetation. Additionally, remote sensing data required processing following collection, meaning it was not available in real-time. Due to the large study area and variability in soil thicknesses and typography, soil moisture probe sensors were also ruled out because of the difficulties and cost of installation. Thus a proxy for soil moisture was used in the model.

The Antecedent Daily Rainfall Index is a proxy for soil moisture and is a weighted tally of rainfall over a set period. The tally is weighted according to an exponential decay formula, where the rainfall yesterday is weighted higher than the previous day and so on. Calculation of the Antecedent Rainfall Index for the purpose of this model is based on the calculation described by Glade et al (2000):

$$r_{a0} = r_1 + 2^d r_2 + 3^d r_3 + \cdots + n^d r_n \tag{1}$$

where r_{a0} = antecedent daily precipitation, based on maximum regional precipitation values (mm) for day 0, d = constant derived from hydrograph recession curves, and n = number of days before day 0. As shown by Glade (1997), the appropriate length of antecedent period was considered to be 10 days ($n = 10$).

4.2.3 Assessment of Recorded Slope Movements

For each individual recorded slope movement, the rainfall conditions on the day of failure (24-hour rainfall total), and the preceding 10 days were gathered. The Antecedent Rainfall Index was also applied to each slope failure.

Records of slope movement gathered by NCTIR were used to compare triggering thresholds to that of Glade et al. (2000). It was found that the thresholds for slope failure in Kaikōura were roughly an order of magnitude lower than those described by Glade et al. (2000). Differences in topography and climate may explain part of the observed variation in triggering thresholds, however the primary reason for the variation is likely related to an increased susceptibly of slopes to rainfall induced failure due to earthquake damage, as suggested above in Section 2. It was not possible to compare pre-quake slope performance in Kaikoura due to insufficient historical data.

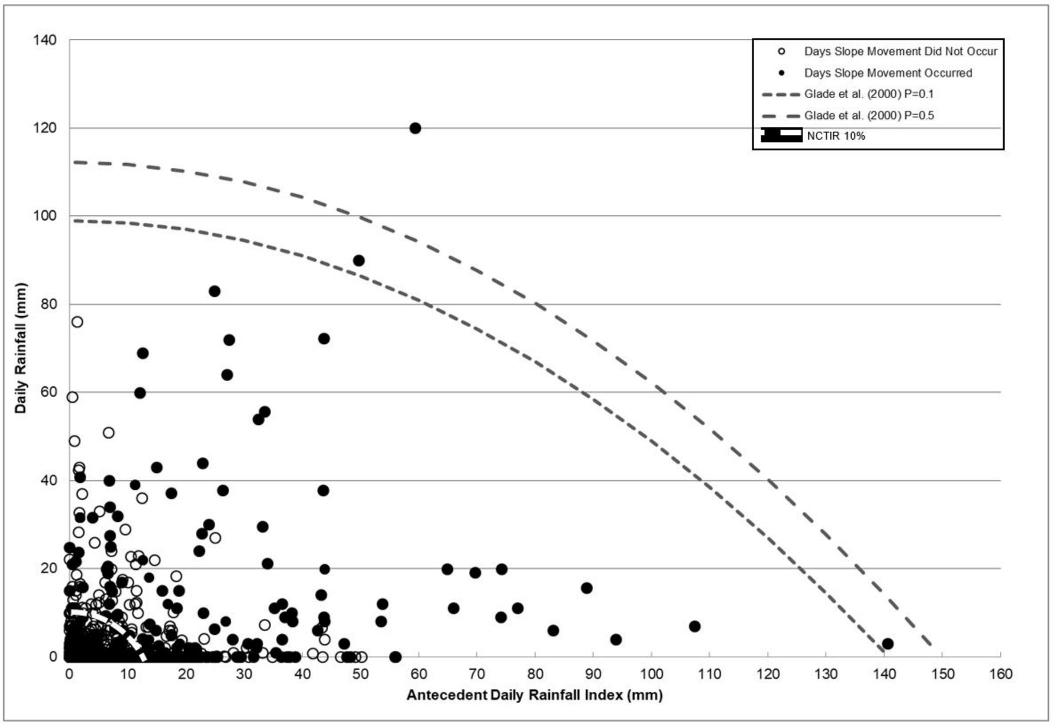

Figure 2: All Slope Movements Recorded by NCTIR since March 2017. Full circles represent days where slope movements were recorded. Hollow circles represent days when no slope movements were recorded.

5 OPERATIONAL USE OF THE MODEL

5.1 IDENTIFICATION OF PROBABILISTIC THRESHOLDS

The probability threshold is a calculation based on the number of events that have been recorded above or below the line. In simple terms, the probabilistic thresholds can be described as the likelihood of failure on any given day. The quality of the input data determines the accuracy of the probabilistic thresholds, and it was found that the threshold probabilities changed over time, likely due to the continuous input of new data and the changing slope characteristics (i.e. changes due to slope failure mitigation works).

5.1.1 Operational Use of Thresholds

Safe management of the MNL through Kaikōura relies upon a suite of operational controls (e.g. speed restrictions, patrols ahead of trains and temporary or permanent rockfall protection measures and the slope failure model detailed in this paper). The probabilistic thresholds developed in this study were used to help rail operators understand the likelihood of slope failure under rainfall events. An assessment of risk during different rainfall events was made possible by comparing the number of failures and the type and size of failures associated with various rainfall conditions. Figure 3 and Table 1 show an example of the information that was presented to the rail operators.

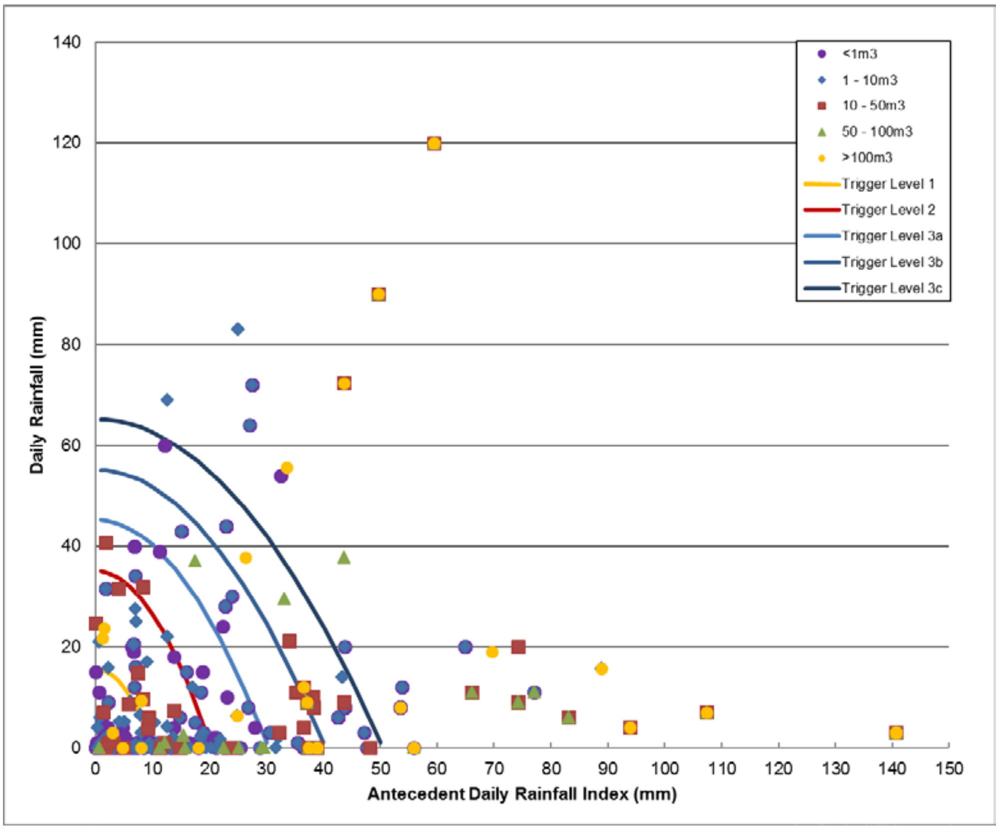

Figure 3: Recorded slope movements since March 2017. Showing the daily and antecedent rainfall conditions associated with each failure. The volume of debris associated with slope movements is also shown. Trigger Levels represent probabilistic thresholds used by the rail operator to aide in risk management decision-making. The probabilities of slope failure for each of the Trigger Levels shown are presented in Table 1.

Table 1: Recorded Slope Failures for Defined Trigger Levels

Trigger Level	Number of Failures	Percentage
Total	863	-
Below Trigger Level 1	180	21%
Between Trigger Level 1 & 2	145	17%
Above Trigger Level 2	538	62%
Above Trigger Level 3a	470	54%
Above Trigger Level 3b	388	45%
Above Trigger Level 3c	263	30%

5.2 APPLICATION OF MODEL AS A FORECASTING TOOL

To enable the rail operator to sufficiently plan alternatives and notify freight customers if a train is unable to be run due to the risk of slope failure, the model was developed into a forecasting tool. Based on rainfall records and rainfall forecast, it was possible to assess the likelihood of slope failure up to three days in advance (for commercial management), using the probabilities of rainfall induced slope failure established by the model.

5.2.1 Forecast of Daily Total Rainfall

As the decision to run a train needs to be made three days ahead of time, a forecast of the 24-hour rainfall totals for the three days ahead was needed. Equally, the Antecedent Daily Rainfall Index data needed to comprise seven days of actual recorded rainfall data and three days of forecasted rainfall data.

To account for orographic effects and geographical variability in rainfall volume, the daily total rainfall was averaged over two geographical areas; north of Kaikōura and south of Kaikōura. Rainfall averages were calculated using numerous weather gauges (including some located adjacent to major earthquake induced landslides).

Rainfall is often difficult to forecast and typically a range of rainfall volumes is provided with a standard forecast (e.g. 10 mm to 20 mm). However, if a range of forecasted rainfall data is used, and it is found to straddle the defined threshold line when plotted, it is not possible to determine an absolute outcome, therefore, only a single value was used in the assessment.

5.2.1 Rainfall Intensity

Rainfall intensity is especially hard to forecast, particularly multiple days ahead of time. For this reason, rainfall intensity is excluded from the early assessment and was instead monitored in real-time by network operators.

5.3 USE AS AN EARLY WARNING SYSTEM

A Trigger Action Response Plan (TARP) was developed to help plan and manage the suite of operational controls that can be implemented to improve operational safety during wet weather. Based on the probabilistic thresholds, the rail operator defined set Trigger Levels that initiate various operational controls (e.g. speed restrictions or patrols ahead of train transits). The rail operator also selected an upper Trigger Level that represented the upper limit to the effectiveness of operational controls, at this point train movements were put on hold and the rail line temporarily closed. Forecasting of the weather conditions ahead of time enabled the rail operator to plan ahead for effective and safe operational management based on the forecasted Trigger Level.

6 CONCLUSIONS

Given the relatively large dataset of slope failure records, it was possible to apply probabilistic thresholds to the Daily Rainfall vs. Antecedent Daily Rainfall Index model, however the accuracy of the probabilistic thresholds was difficult to fully assess due to several limitations. Firstly, collection of slope mobilisation data occurred concurrently with numerous construction and slope stabilisation activities throughout the affected transport corridor, therefore the recorded frequency of slope instabilities was affected by the efforts to reduce or mitigate slope instability. Secondly, the data inputs for the model are limited to 24 hour totals that are averaged over wide geographical areas, therefore rainfall events with varying intensity and varying temporal and spatial patterns are not considered in the model. The specific limits of accuracy of the model have not yet been well established, however use of the model as a risk management tool, in the absence of an alternative, has been found to be effective. Further refinement of the model could include an assessment of hydrographs specific to Kaikōura to further understand the decay constant used in the Antecedent Daily Rainfall Index.

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