The use of Trigger Action Response Plans to mitigate wave overtopping hazard on coastal infrastructure

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Abstract
Wave overtopping of coastal infrastructure such as rail, road and shared pathways can be hazardous to users and potentially threaten structural integrity and reliability. A Trigger Action Response Plan (TARP) provides a robust framework for mitigating risk by defining response actions based on escalating trigger levels. These actions, and their expected frequency of occurrence can be implemented into construction or operational programs and adjusted as new data becomes available or engineering modifications are made.

This paper presents an overview of this framework applied to a case study at Ōhau Point, north of Kaikoūra, New Zealand. This site was significantly impacted during the November 2016 magnitude 7.8 earthquake with a large landslip inundating both the State Highway 1 road and Main North Line rail corridors. Recovery works undertaken by the North Canterbury Transport Infrastructure Recovery (NCTIR) Alliance reinstated the roadway further seaward and at a lower level than previous due to residual landslide and rockfall risk. A unique combination of steep offshore bathymetry and rock outcrops resulted in focusing of wave energy and overtopping to occur at a higher frequency and magnitude than expected. This overtopping posed risks to the recovery team and the public and potentially to the structure itself during extreme events.

A work programme was initiated to investigate and mitigate this risk. This comprised field data collection including detailed bathymetric and topographic surveys, an offshore wave buoy and camera system, numerical wave hindcast, development of image processing techniques to automatically detect overtopping events and physical modelling of the 3D environment to quantify overtopping flows during typical and extreme events. The programme resulted in the development of a Trigger Action Response Plan (TARP) defining threshold wave and water level conditions for a range of actions including traffic management, road closure and post-event structural inspection. This TARP was successfully used to manage risk while longer term mitigation measures were tested and implemented. The TARP was then modified to incorporate the reduced overtopping magnitude and frequency resulting from the engineering works.

Keywords: wave overtopping, hazard, risk mitigation, image processing, physical modelling

1. Introduction

Trigger Action Response Plans (TARPs) are well established tools used to manage risk in mining applications [5]. A TARP defines a set of trigger levels related to a particular hazard, along with the associated responses to be initiated when that trigger level is reached. Bakker [1] identifies that an effective TARP must balance operation while safely managing risk. Once in place, TARPs are continually optimised as the understanding of the hazard improves and more information becomes available, or the works layout changes.

Following the November 2016 Mw7.8 Kaikoūra earthquake sequence, the TARP concept was adopted by the North Canterbury Transport Infrastructure Recovery Alliance (NCTIR) to manage slope failure risk [4]. These TARPs utilised probabilistic thresholds established based on rainfall-slope failure relationships derived for the Kaikoūra region. Once rainfall triggers were forecast, construction activities could be appropriately managed.

The site at Ōhau Point, north of Kaikoūra, New Zealand was significantly impacted during the November 2016 earthquake with over 50,000 m^3 of rock and soil inundating both the State Highway 1 road and Main North Line rail corridors [4] (Figure 1A). Recovery works undertaken by the NCTIR Alliance reinstated the roadway further seaward and at a lower level than previous due to residual landslide and rockfall risk and seismic constraints of the seawall design. The seawall, on which the roadway is constructed, comprises precast concrete blocks placed on a mass concrete foundation backed by layers of fill and geogrid (Figure 1B). The seawall is terminated with a seawall capping block at an elevation of around RL9.6m (approximately mean sea level).

A unique combination of steep offshore bathymetry and rock outcrops results in focusing of wave energy at the site. Overtopping was observed during the construction phase and following construction at a higher frequency and magnitude than expected (Figure 2). Comparisons between overtopping volumes inferred from site video and photographs and predictions based on empirical guidance indicates under-prediction of mean flows by an order of magnitude. This is expected due to the highly three-dimensional nature of the overtopping process at this site compared to the 2D data upon which empirical guidance is based.

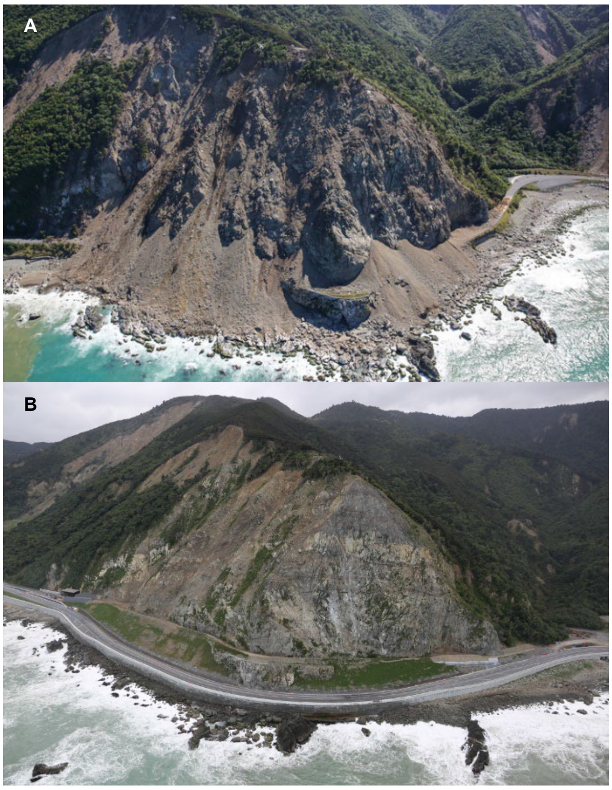

Figure 1 Ohau Point immediately following the Nov 2016 Earthquake (B) and near seawall completion in June 2018 (B).

Figure 2 Example of overtopping events at Ohau Point during construction on 7-9 Jan 2018 (A, B), on 8 July 2019 (C, D), 25 July 2019 (E) and 15 August 2019 (F). Source: NCTIR

This overtopping posed risks to the recovery team and the public and potentially to the structure itself. Investigations were initiated to both understand and mitigate the immediate overtopping risk, as well as to develop longer-term mitigation strategies to achieve a level of service commiserate with agreed targets for the wider project.

2. Data collection

2.1 Topography and bathymetry

Existing topographic LiDAR and offshore multibeam sonar was supplemented with high resolution photogrammetry above low tide and 'drone dipping' in the nearshore. This method, developed on the NCTIR project, utilises an RTK GPS-equipped unmanned aerial vehicle (UAV) and dips a weighted line of known length until the seabed is encountered. This method provides highly accurate (<5cm vertical / 10cm horizontal resolution) bathymetric information while minimising constraints associated with weather, access and safe navigation. These sources were combined into a composite digital elevation model (Figure 3).

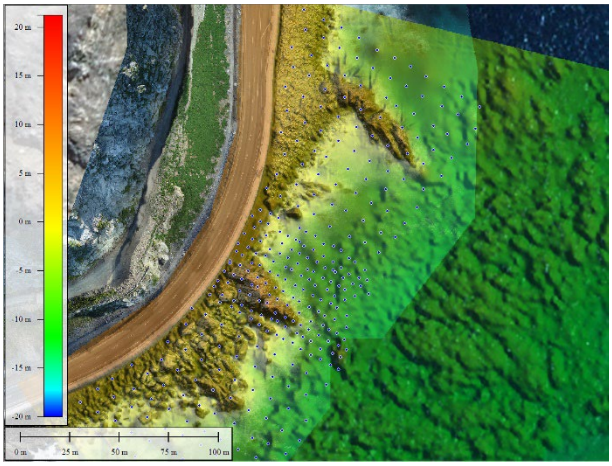

Figure 3 Digital elevation model combining photogrammetry on land, multibeam offshore and 'drone-dipping' points in the nearshore (defined by blue dots)

2.2 Waves and water levels

A 40-year wave and water level hindcast was undertaken by Metocean Solutions Ltd (1979 – 2019). This hindcast provided wave and water level timeseries and summary statistics information for a location offshore of Ohau Point in approximately 50m water depth. Additional observed water level data available from a Land Information New Zealand tide gauge located on the Kaikoura Peninsula.

A Sofar Spotter wave buoy was deployed offshore of Ōhau Point in November 2019. This data is compared to wave information derived from a Metocean nowcast over the same period (Figure 4) with an RMS difference in wave height in the order of 0.25m providing confidence that forecast data would be suitable for use in identifying when TARP trigger points are likely to be reached.

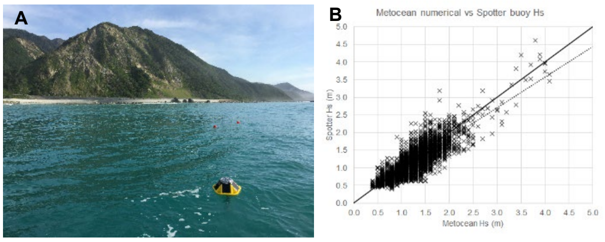

Figure 4 Spotter wave buoy installed offshore of Ohau Point (A) and compared to nowcast data (B)

2.3 Camera system

A fixed point camera was established overlooking the critical overtopping point at Ōhau Point (Figure 5). The camera captures images at 1 second intervals for the first 20 minutes of each hour. The imagery is intended to provide a record of when overtopping occurs and its extent.

Figure 5 Camera installed at Ōhau Point (circled)

An image analysis tool was developed to assist in detecting overtopping. This tool first determines the maximum pixel intensity over 20mins of imagery (Figure 6A) which provides indication of whether an overtopping event has occurred during the 20 min sample. The pixels along a row corresponding to the critical overtopping location are extracted and stacked together (Figure 6B). This 'timestack' of pixel intensity shows whitewater location and, when pixel intensity is extracted at specific locations (Figure 6C), a threshold can be used to automatically detect overtopping events and original images identified (Figure 6D) to confirm overtopping occurrence and severity.

2.4 Physical modelling

Physical model testing was undertaken to better understand the likely performance of the seawall under extreme conditions at current and future sea levels and testing and optimisation of a range of mitigation options. The physical model testing is described in detail within [3] but, given the complexity of nearshore wave and overtopping processes, a quasi-3D model was constructed in a 3m wide wave flume to allow for these processes to be adequately simulated (Figure 7).

Testing was undertaken for a previously observed event (19 August 2019 – refer Figure 7) as a control case with good visual agreement and overtopping volumes similar to those estimated from video. Wave overtopping was measured during a range of wave heights (1.5 – 4m), wave periods (11-17s) and water levels (MSL to MHWS + 0.5m) to characterise the overtopping flows during a range of potential conditions (i.e Figure 8) and assist in deriving wave height and water level-based trigger levels. Additionally, testing of extreme conditions under current and future sea levels was undertaken to assist in developing engineering options for mitigation.

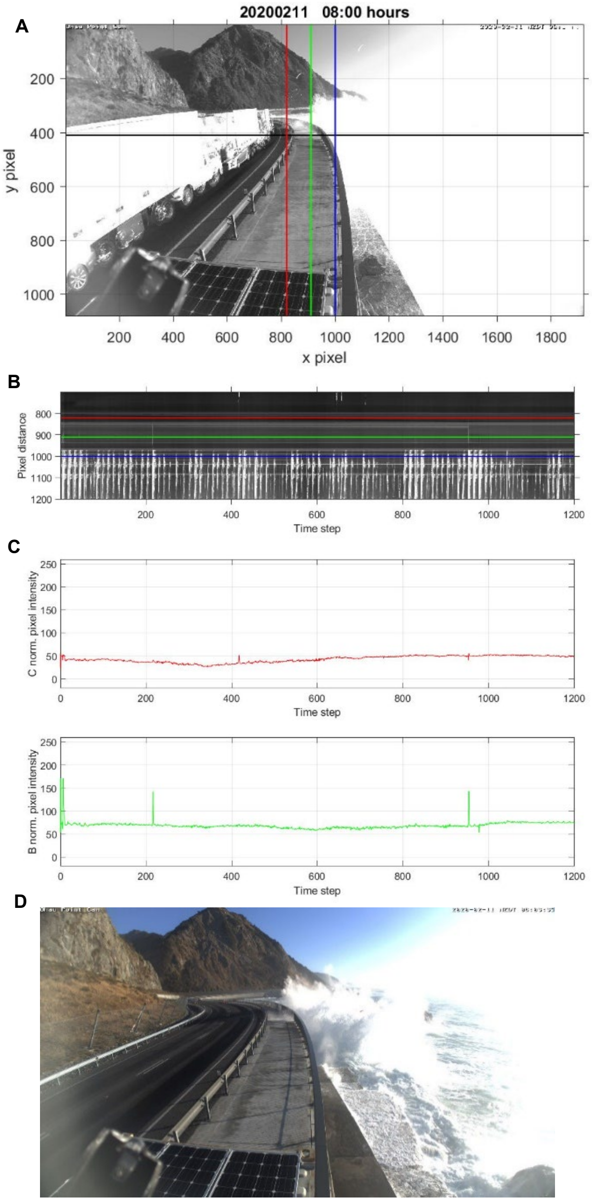

Figure 6 Example output from the tool developed to automatically detect overtopping in camera imagery.

3. TARP Development

A TARP required a set of trigger levels related to a particular hazard to be identified, along with the associated responses to be initiated when that trigger level is reached. These triggers and the response could be validated against field data and refined as needed (Figure 9).

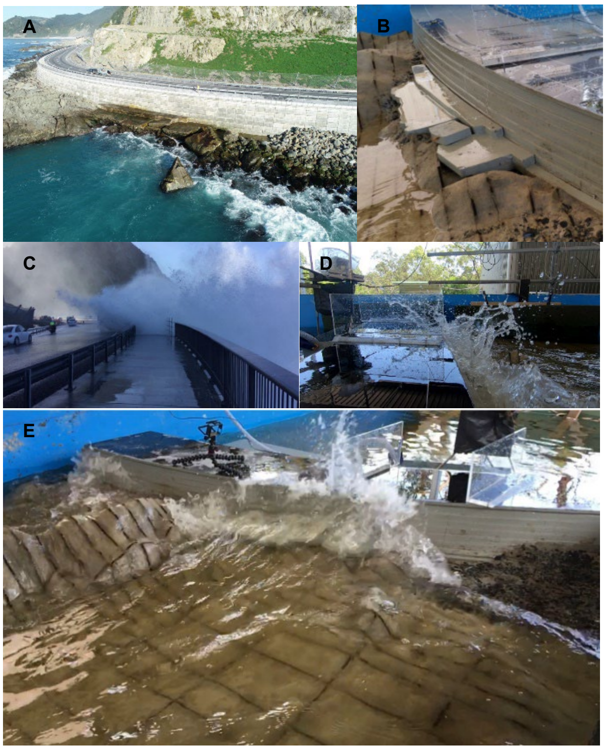

Figure 7 Example of the prototype and modelled seawall (A-B) and of observed and simulated overtopping during August 2019 event (C-E).

3.1 Establishing overtopping thresholds

Overtopping hazard is generally defined according to mean and maximum flow rates (q_{mean} and V_{max}). Literature [2] identifies tolerable overtopping rates for various applications including pedestrian and vehicle safety and structural integrity. Additionally, the NCTIR project had defined minimum standards [6] applicable across the project. Mean overtopping rates were therefore utilised to define a low (0.1 – 1 l/s/m), moderate (1 – 5 l/s/m), high (5-10 l/s/m) and severe (>10 l/s/m) levels of overtopping with expected impacts.

The complex overtopping process at Ohau Point was not well represented by empirical guidance and instead the results of physical modelling was initially used to relate wave characteristics and water level to overtopping. Wave height was identified as the most important wave characteristic influencing overtopping (Figure 8) and, in order to simplify the process, was adopted along with tide level as the threshold for the various triggers.

The implication of the selected thresholds in terms of frequency of occurrence could be evaluated using hindcast data. It was found that the lowest level of overtopping would occur, on average, once every 2 weeks, with moderate overtopping occurring one per month, high overtopping once every 6 months and severe overtopping once every 5 years on average. This was compared to reported frequency of overtopping at different levels since road completion with good agreement. This was below the level of service required for the project and options for further mitigation were developed (refer Section 3.4 and [3]).

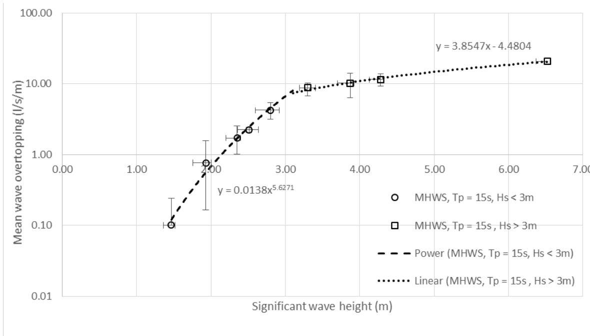

Figure 8 Example of measured mean overtopping rate for a range of wave heights during a MHWS water level.

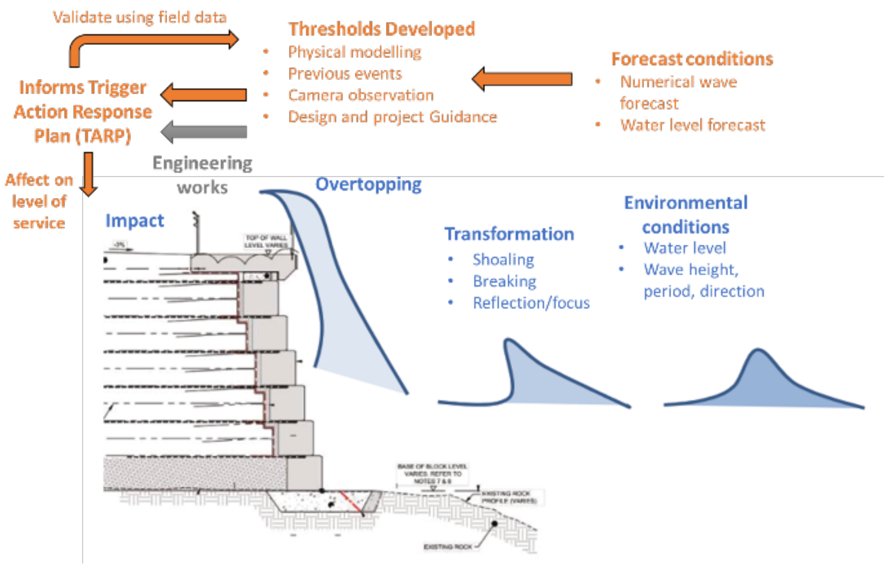

Figure 9 Coastal processes leading to overtopping (Blue) with the approach utilised in setting thresholds to inform the Trigger Action Response Plan (Orange) and finally modified by further engineering works (Grey).

3.2 Setting action response

Responses appropriate to the level of risk for each trigger level were developed. At the lowest overtopping level (Level 1), the network outage contractor was made aware and warning signage could be deployed at discretion. At the moderate level (Level 2), signage should be deployed, access to the shoulder restricted and speed reduced to 50 km/hr. Safe hit posts were installed along the centreline to improve lane delineation. At high levels of overtopping (Level 3), along with the above speed was reduced to 30 km/hr, single lane operation may occur with stop-go at high tide as required. At severe levels of overtopping (Level 4) single lane and stop-go may be required during all tides with stop-stop (road closure) potentially required during high tide.

Previous overtopping events, the observed impacts on site and the suggested appropriate response based on reports from traffic management personnel on site were used to validate the selected response measures.

3.3 Overtopping prediction and validation

Once thresholds had been established, forecast models for wave height and water level could be used to predict upcoming overtopping events based on trigger levels. These forecasts could then be validated using imagery and wave buoy and water level gauge data available at the nowcast time. Some difficulties were encountered in using camera imagery including lack of data during night or other adverse lighting conditions (i.e. glare), overtopping occurring outside the first 20mins of the hour as often only larger sets of waves caused overtopping and even with a camera frequency of 1 fps, the magnitude or extent of individual events could be missed.

Figure 10 shows the level of overtopping observed over a 10-month record compared to the initial TARP thresholds. Cases where no overtopping was observed are also identified along with ‘incipient’ overtopping where minor spray may occur but doesn’t meet the low threshold. From results, it is evident that overtopping could from time to occur at lower wave height and water level thresholds than initially defined but also that no overtopping could occur at higher thresholds. There are likely to be a range of explanations for this including: inaccurate nowcast information (though comparisons against wave buoy and water level gauge data show similar scatter); additional factors such as wave period and direction; groupiness unaccounted for in the spectral wave characteristics; limitations in observing overtopping due to the camera shortcoming described above and/or user error in designating overtopping level.

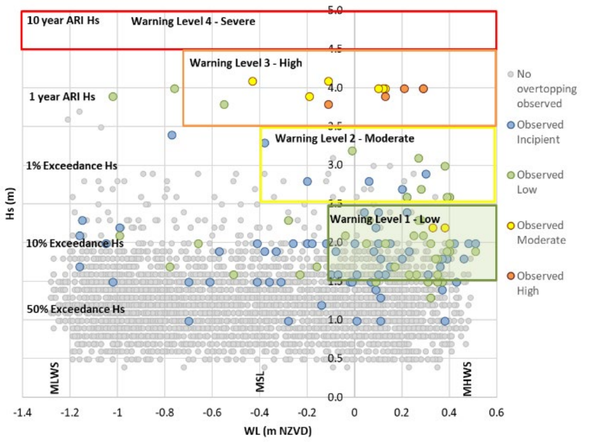

Figure 10 Observed overtopping events as a function of nowcast Hs and WL. Incipient events are levels of overtopping below the criteria for low level. Coloured boxes represent the initial TARP threshold criteria

On this basis, the warning thresholds were slightly revised, particularly for the lower thresholds with the low level threshold increasing to Hs = 2m and moderate level to Hs = 3m. The ‘initial’ TARP was then updated to produce a ‘validated’ TARP. In undertaking this validation, it was found to be important to identify the conditions when overtopping was not occurring as well as when it was and also to only consider conditions occurring when accurate image data was available. Figure 11 shows an example of an event with the initial and validated criteria used to predict overtopping level compared with observed (i.e. Figure 12).

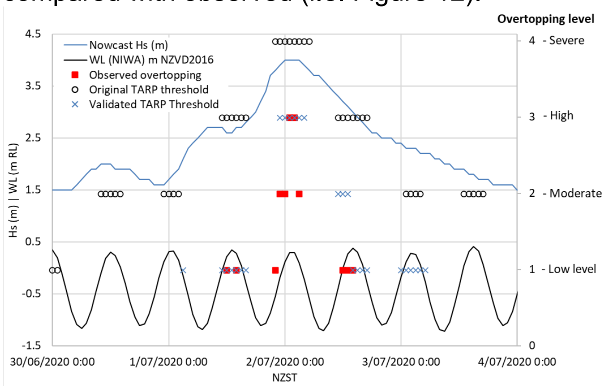

Figure 11 Predicted overtopping levels based on wave height and water level using the initial and the validated criteria compared observed levels.

Figure 12 Example of low level overtopping identified at 2pm on 2/7/20

3.4 Effect of mitigation works

A range of potential engineering works to further mitigate the long-term hazard were tested as described within [3]. These included addition of a 1.2 m high crown wall, removal of concrete slabs fronting the structure (which were observed to form a ramp for incoming waves) and construction of a toe revetment using concrete 'hanbar' armour units. These works were all found to generally reduce measured overtopping volume and therefore could be inferred to increase the wave height at which a threshold or trigger was reached.

A 1.2m high crown wall was selected as the preferred option (Figure 13). This was found during physical modelling to reduce overtopping to around 40% of the existing situation and allowed wave height thresholds for TARP triggers to be increased by around 0.5m. This change reduced the frequency of a required response by around 50% resulting in significant potential cost savings over the project life as well as improving safety and resilience of the infrastructure.

Figure 13 Installation of a crown wall at Ohau Point

The final 'modified TARP' (Table 1) should be further refined over time as additional data becomes available and operational responses are optimised.

4. Summary and recommendations

A Trigger Action Response Plan (TARP) provides a useful tool for managing overtopping hazard. While TARPs are well established tools used to manage risk in mining and slope stability applications, this is, to our knowledge, the first example of use to manage coastal hazards.

The overtopping at Ohau Point was a complex, three-dimensional process not well represented by empirical guidance. Physical modelling allowed accurate representation of this process and assessment of likely performance under typical and extreme conditions at current and future sea levels as well as testing and optimisation of a range of mitigation options. This greatly assisted in setting preliminary thresholds for a range of trigger levels without having to have observed these events in the prototype.

A camera system provided near-real time imagery and information on overtopping using image processing. This, combined with wave buoy data and forecast information enabled the initial TARP to be validated using site-specific data. In refining thresholds, it was found to be important to identify the conditions when overtopping was not occurring as well as when overtopping was. The TARP was further modified once mitigation works in the form of a crown wall with angled return was constructed.

While image processing assisted in identifying the occurrence of overtopping, manual interpretation was still required to determine the level of severity. While the level of severity was approximated to an overtopping discharge, this was not possible quantitatively and therefore remains a weak point in linking site observation with laboratory results and theoretical 'tolerable' overtopping values. In the authors opinion, q_{mean} rates reported in literature have little relevance in complex, 3D environments such as this and more emphasis and effort should be placed on quantifying maximum individual flow characteristics and relating this to user comfort and hazard. Given the often site-specific nature of overtopping, further development of empirical models may not be helpful, but rather improvement of data collection methods and alignment between observation and design parameters.

5. Acknowledgements

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6. References

[1] Bakken, K., Chapin, G. & Abrahams, M. (2020) Trigger action response plan development and optimisation at the Bingham Canyon Mine. Proc. of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering, Australian Centre for Geomechanics, Perth.

[2] Eurotop (2007), Wave Overtopping of Sea Defences and Related Structures, Assessment Manual.

[3] Flocard, F., Deiber, M., Shand, T., Blacka, M., Knook, P. and Proctor, S. (2021) Physical modelling of complex overtopping flows at Ōhau Point, Kaikōura and development of mitigation measures. Australasian Coasts & Ports 2021 Conference, Christchurch, New Zealand.

[4] Mason, D., Justice, R. and Saul, G. (2018) Kaikōura Earthquake Slope Hazards – Risk Mitigation and Network Resilience. NZ Geomechanic News, 96, Dec 2018

[5] MBIE (2013) Guidance for a Hazard Management System for Mines

[6] NCTIR (2017) Schedule 5 - Requirements and Minimum Standards (100001-GE-GE-SH-0001[A]PAA)

Table 1 Ōhau Point Wave Overtopping Trigger Action Response Plan (TARP) for situation with crown wall complete

Warning Level	**Warning Threshold**[2]	**Wave overtopping level**	**Example**[3]	**Impact**	**TARP response**
• **Level 1** Occurrence: Average ~once/3 weeks (though action could be required on consecutive high tides)	• Wave height 2.0 – 3.0m • Within 3 hours either side of high tide	Low (q_{mean} = 0.1 l/s/m)		• Spray onto capping beam and may reach edge of road • Overtopping occurs infrequently (<20min between events) • Uncomfortable but not dangerous for aware pedestrians/cyclists. • No major risk to traffic though potentially distracting at high speed	• NOC aware • Deploy wave warning signage at discretion
• **Level 2** Occurrence: Average ~once/2 months (though action could be required on consecutive high tides)	• Wave height 3.0 - 4.0m • 3 hours either side of high tide	Moderate (q_{mean} = 1 l/s/m)		• Whitewater splashing over capping beam and onto road. Some sheet flow (<50mm depth) over road • Occurs semi-frequently (10-20min between overtopping events) • May be dangerous to pedestrians/cyclists. • May be distracting to drivers and dangerous at high speed	• Deploy wave warning signage to alert drivers • Restrict access to shoulder • Speed reduction to 50 km/hr
• **Level 3** Occurrence: Average ~once/2 years (though action could be required on consecutive high tides)	• Wave height 4.0 – 5.0m • 4 hours either side of high tide	High (q_{mean} = 5 l/s/m)		• Significant whitewater across road. Sheet flow up to 100mm depth. • Occurs frequently (5-10 min between overtopping events) • Dangerous to pedestrians/cyclists. • Dangerous to drivers at any speed	• Deploy wave warning signage • Close the shoulder • Speed Reduction 30km/h • Single Lane Operation – using northbound lane • Stop / Go • Stop / Stop at Peak tide
• **Level 4** Occurrence: Average ~ once/10 years	• Wave height Threshold > 5m • All tides	Severe (q_{mean} > 10 l/s/m)		• Significant greenwater over road (flows likely >0.3m depth) • Occurs very frequently (<5 min between overtopping events) • Extremely dangerous for pedestrians/cyclists • Extremely dangerous for vehicles • Likely some damage to road or fixtures	• Deploy wave warning signage • Close road / shoulder • Use single lane Stop / Go operation during low tides, using northbound lane. • With Stop / Stop as required.

[1]Works include installation of crown wall [2]Warning thresholds are assumed to be based on *general sea area forecast* [3]Examples from before NCTIR works completed