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Tsunami and their potential effects on critical infrastructure

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ABSTRACT

Critical infrastructure is fundamental to sustaining societies and economies. Tsunami and earthquakes pose an increasing threat to the effective functioning of infrastructure worldwide.

Pacific Island Communities (PIC) are some of the world's most vulnerable, and resilience is now one of the most critical challenges faced. There is growing demand for effective sustainability and resilience concepts. Tonkin + Taylor works at the forefront of assessing and managing natural hazards and risk in the New Zealand and Pacific region, as well as post-event recovery.

This paper highlights critical infrastructure risk assessment for tsunami and earthquakes. We present evidence-based, risk-informed approaches to adapting critical infrastructure to meet the threats, along with determining appropriate performance criteria for infrastructure risk reduction and building community resilience.

Large or Great Earthquakes are often catalysts for deadly after effects that cause great damage to PIC. They can have major effects on vulnerable communities and the built environment, with tsunami typically causing by far the greatest destruction. If the main shock event does not cause significant damage, subsequent aftershocks, with their repeated shaking, often pose greater risk to the built environment and infrastructure. Volcanic eruptions have more recently been observed following major earthquakes such as the M7.5 28 September 2018 Palu, Indonesian event with volcanic activity being reactivated, causing environmental issues as well to local communities.

With better understanding of hazards to post-recovery response and reducing stress from such natural disasters, such communities are better able to re-build and function quickly and effectively to manage their long-term return to life post-disaster.

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1 INTRODUCTION

Extreme natural events, such as tsunamis or earthquakes, regularly lead to catastrophes with severe impacts on infrastructure. In more recent tsunamis in Indonesia as well as the devastating 2004 Boxing Day tsunami caused hundreds of thousands of deaths, destruction of infrastructure, disruption of economic activity and loss of billions of dollars' worth of property. This paper highlights critical infrastructure risk assessment for tsunami and earthquake.

The current state-of-practice for tsunami hazard mapping for coastal communities mainly considers tsunami hazard parameters (such as inundation depths and arrival times of major tsunami waves) that correspond to a single or at most, a few scenarios on a selected fault. This approach lacks comprehensive information on the uncertainty of these hazard predictions. Consequently, the range of inundated areas and required structural design criteria cannot be adequately quantified, which in turn hampers the risk communications between tsunami analysts and local stakeholders. Therefore, users of scenario-based tsunami hazard maps may not be able to appreciate the potential risks (and their uncertainties) under different conditions. Many examples exist, such as 2011 Tohoku, Japan tsunami, with more than 65% of all fatalities in Kamaishi, and the 2018 eruption of Anak Krakatau, Indonesia tsunami that killed 426 people and damaged several infrastructure. We can better assess the risks of tsunamis on critical infrastructure through a better understanding of the holistic interactions of infrastructure networks, but also through an improved understanding of the failure modes of individual structures. There are several methods and models in use, among them some more interesting than others.

Pacific Island Communities (PIC) are most vulnerable to natural disasters, often with a lack of streamlined disaster management that is readily available or even implemented during and post disaster. This makes recovery, both immediate and long-term, often difficult and cumbersome. Improving such communities' resilience to natural disasters with government policy, preparedness, simulations and post-disaster recovery/response all contribute to detailed and appropriate methods implemented by both locals and external on-call agencies at the time of such events. Tonkin + Taylor have led several workshops with local communities at the grassroots level to better prepare them for such events and to provide necessary tools in rebuilding devastation that is often accompanied post-event.

2 PROBABILISTIC TSUNAMI HAZARD ANALYSIS

One of the major challenges for tsunami impact assessment is to predict the earthquake source characteristics of future tsunamigenic events (such as location, magnitude, and slip distribution), and to then quantify the uncertainty associated with the variability in earthquake rupture and wave propagation/inundation processes (Nobuhito et al., 2017). In particular, tsunami propagation and inland inundation characteristics are greatly influenced by complex and nonlinear interaction of earthquake source properties and changes in bathymetry and land elevation. Probabilistic Tsunami Hazard Analysis (PTHA) is a viable approach to identify tsunami source regions and corresponding scenarios that have major impacts to the site of interest (Fukutani et al., 2015, Mueller et al., 2015, Park and Cox, 2016). Recently, the American Society of Civil Engineers (ASCE) announced the new Chapter 6 (6.7 Inundation Depth and Flow Velocity Based on Site-Specific Probabilistic Tsunami Hazard Analysis) to introduce design requirements for tsunami loads and their effects (Chock, 2016) that can be defined through PTHA. Therefore, the role of PTHA becomes more important in both scientific and engineering fields.

Attempts are being made to better understand the interrelated, cascading risks of natural disasters to critical infrastructure by adopting a systems-based approach. Wang et al. (2018) modelled the impact of different classes of attacks on a combined, interdependent system of the road and railway networks in China. The authors introduced an "oriented local attack" mode to give directionality to the propagation of failures through the network. This approach allows for simulating natural disasters with a directional element, for example the path of a tornado or the inland movement of a tsunami wave. The authors found that this attack mode was more disruptive than a random or a non-directional attack mode, and comparable to a malicious attack mode (which assumes an active, knowledgeable attacker attempting to maximise damage to the system). This is because an oriented local attack tends to result in the fragmentation of the network into sub-networks, preventing flow between certain areas. This aligns with real-world experiences, such as in Aceh Province in Indonesia, where communities were isolated by the tsunami destroying bridges and water pipelines (Ghobarah et al., 2006).

Novel modelling techniques also offer the potential to enhance tsunami risk assessment. Yang et al. (2017) used the material point method approach to model the loads caused by tsunami-driven debris on bridge superstructures. This approach offers the benefit of being able to cope well with solid and fluid objects simultaneously, which has obvious benefits for modelling debris movement. Previous approaches have focussed on just the effects of water, or analysed debris in terms of the moment of impact, with little or no attention paid to effects such as pressure induced by debris damming. The authors found that the loads on bridges using their approach were 25-35% higher than using an in-air analytical approach.

3 TSUNAMI RISK ASSESSMENT METHOD

The American Society of Civil Engineers (ASCE 7) tsunami loads and effects subcommittee has issued a revised chapter for the ASCE/SEI 7 Standard, Minimum Design Loads for Buildings and Other Structures (ASCE 7, 2016). These are the latest tsunami design provisions available.

For determining the tsunami depths and flow velocity based on run-up at a port site, we selected ASCE 7 tsunami loads and effects design standard using Energy Grade Line Analysis (EGLA). The EGLA takes the tsunami amplitude offshore at the coast as the start of a hydraulic analysis along a topographic transect from the shoreline to the run-up point (Figure 1). As we had tsunami amplitude information at the coast, we started the EGLA analysis from the coastal boundary.

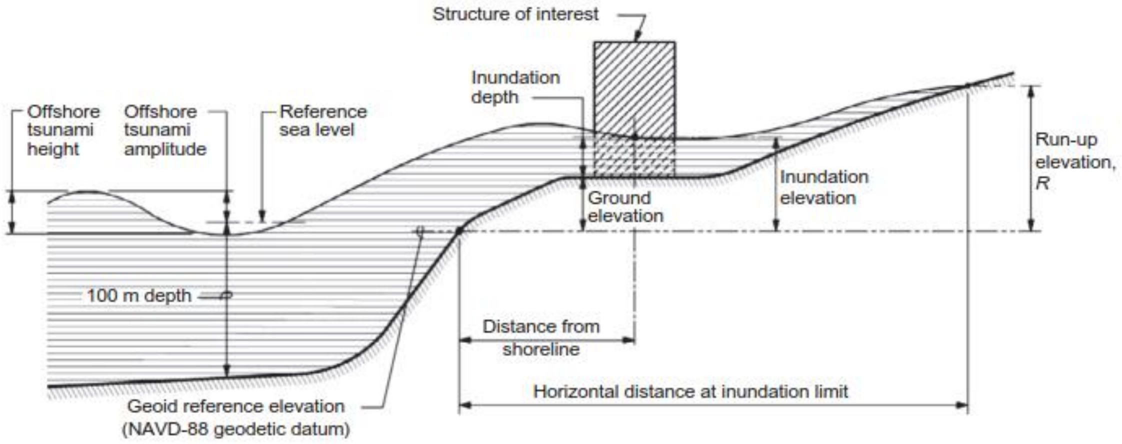

Figure 1: Illustration of the principles of the energy grade line analysis (ASCE 7, 2016)

The EGLA has been developed to produce conservative design flow parameters from the coast to the port structure area by the use of one-dimensional linear transects along a topographic (LIDAR) profile.

The Energy Grade Line determines the variation of inundation depth and associated flow velocity across the inland profile. Velocity is assumed to be a function of inundation depth, calibrated to the Froude number that is prescribed to decay gradually based on distance from the shoreline along the transect, calculated according to Equation 1:

$$F_r = \alpha \left(1 - \frac{x}{x_R}\right)^{0.5} \tag{1}$$

Where Froude number coefficient, α is set equal to 1.0 for areas where bore conditions do not exist. Where bore conditions do exist, a greater value of 1.3 is warranted. For this assessment we used 1.0 as bores are unlikely to occur on the open coast and wide harbours. They may occur along the Marlborough Sounds due to the steep narrow channels, but at this location the tsunami height was less than 2 m.

3.1 Types of variables and inputs

There are different types of variables used for EGLA. The procedure follows three steps as set out below.

STEP 1: Set all the fixed inputs

This step consists of setting all variables which stay fixed during the calculation. Those variables are:

- Apparent Zmax (m): (tsunami amplitude) as obtained from the GNS database
- Run-up elevation, R (m): This value is deduced from the DEM data from the selected near Port point
- Inland inundation distance from coast, expressed as XR (m): This variable can be obtained from the DEM data
- Gravitational acceleration, g = 9.8 m/s^2

STEP 2: Insert all input data

These inputs are known from the available data and can depend on each type of profile of interest for the calculation.

- Distance from the coastal boundary to inland (m)
- Elevation z (m): The elevation values take into account the elevation along the selected profile perpendicular to the tsunami crest
- Manning coefficient set as ɳ = 0.01 (ASCE 7, 2015)

STEP 3: Calculate all the required variables

This step leads to the energy calculation and is highly dependent on steps 1 and 2. In this step there are still some operations that need to be completed before reaching the final energy value. These are:

- Inundation depth at point i: hi = Egi + 1/(1 + 0.5 Fr^2)
- Froude number (Fr): Fri = $(1 - x/xR)^{0.5}$
- Where: x= Distance from the coastal boundary to inland; xR = Inland inundation distance from coast
- Ground slope (ϕi) = Δz/Δx
- Where: Δz = zi – zi + 1; and Δx = xi – xi + 1
- Friction slope (S): Si = $gFr^2/((1/ɳ)\ hi^{1/3})$
- Where: g= gravity acceleration; Fr = Froude number; ɳ = Manning coefficient and hi = inundation depth at point i
- Velocity (u): u = Fri*$((ghi)^{0.5})$
- Energy head (Eg): (Eg I + 1) = Egi - (ϕi + si) Δxi

It is reported by Naito et al. (2016) that the initial design velocity cannot exceed 15.2 m/s or be less than 3 m/s. At Eastland Port the initial design velocity maxima were exceeded at the open coast boundary and were ignored.

4 TSUNAMI RISK ASSESSMENT – CASE STUDY

A case for CenterPort Wellington is shown here as an example. Based on M_w 8.9-9.0 for Hikurangi Margin earthquake scenarios expected to generate maximum credible tsunamis we considered to understand the hazard situation. The exposure area was mostly infrastructure within the port area. The study assessed the critical nearshore tsunami amplitude, momentum and velocity for the port.

CentrePort is located on the eastern side of Wellington Harbour at the southern end of the North Island (Figure 2). It is sheltered from the south facing 2 km wide entrance of the harbour by the Mirimar Peninsula.

The tsunami amplitude at CentrePort is 5.2 m RL with the transect along the tsunami propagation direction shown in Figure 2. The maximum velocity at the shore near the harbour shoreline is 15.0 m/s (Figure 3). The wave continues until it hits the hills behind the port. The energy head difference is shown in the city along the transect line in Figure 4 and momentum flux in Figure 5.

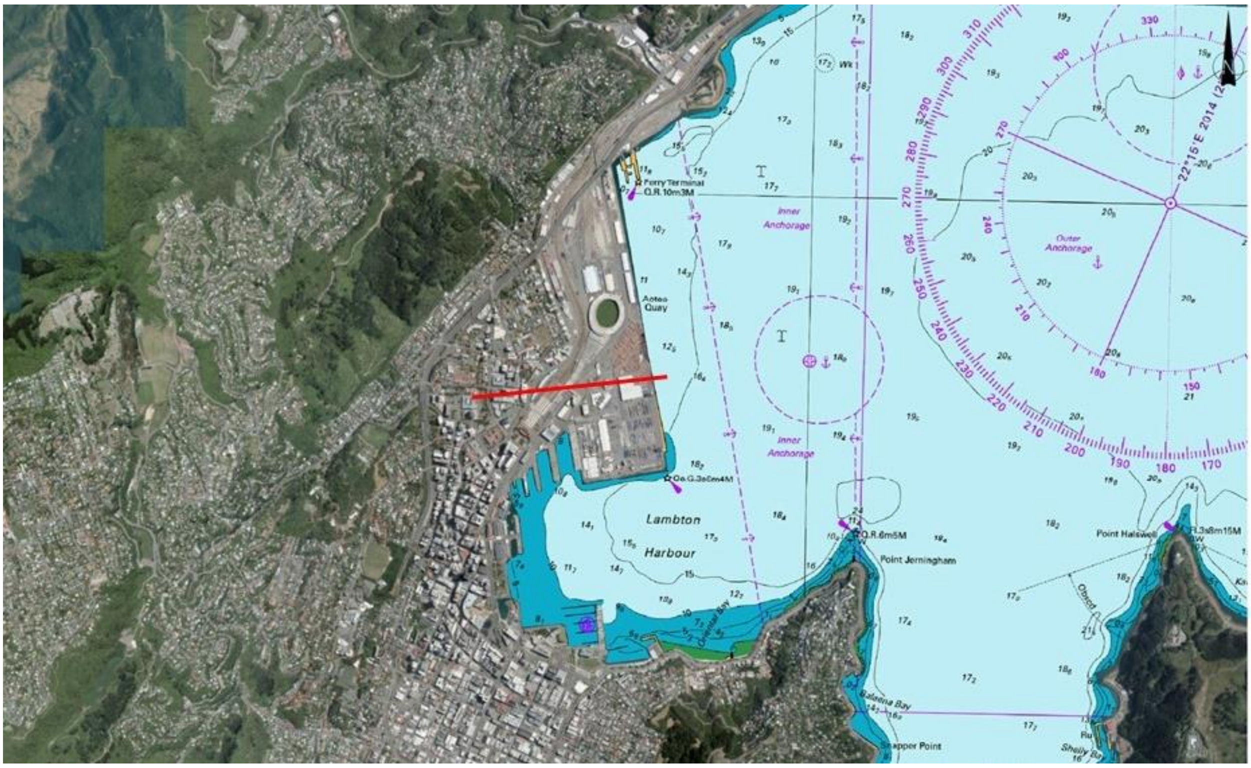

Figure 2: Hydrographic overview of CentrePort (Wellington) and transect (red line)

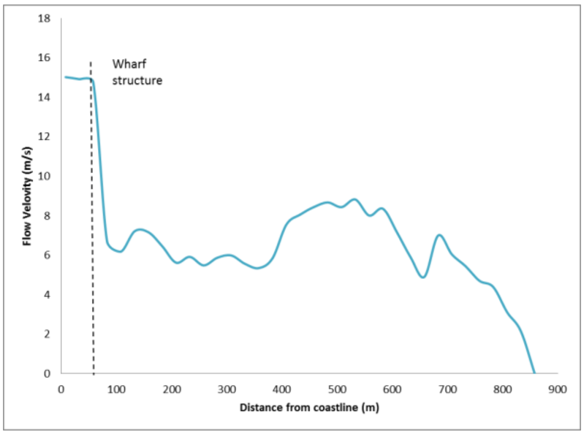

Figure 3: Flow velocity along the transect line

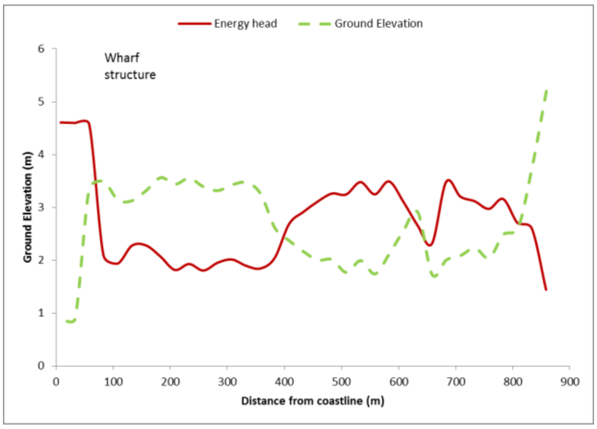

Figure 4: Energy head difference along the transect

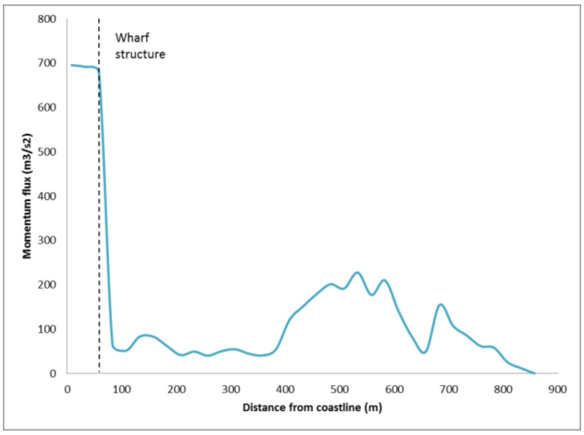

Figure 5: Momentum flux along the transect

5 VULNERABILITY OF PACIFIC ISLAND COMMUNITIES

Small nations dotted along the Pacific ‘Ring of Fire’ are most vulnerable to natural disasters (particularly earthquake, tsunami, volcano and cyclone) with Governments either not having effective policies on Disaster & Risk Management, or policies that are simply not effective for locals at the time of such events. Tonkin + Taylor work at the forefront of assisting in policy at the government level, but also by hosting workshops on simulations/scenarios and testing at grass-roots level involving PIC at a granular level to better prepare them for such events and their immediate responses post-event. Workshops have been held in Tonga and Samoa in meteorological departments to improve current forecasting systems, designing and installing new systems. In Vanuatu, Tonkin + Taylor held workshops in multi-hazard impact based ‘Early Warning Systems’ to a mix of policy makers, financial risk managers and development partners to strengthen regional collaboration in the Pacific and provide best practices to vulnerable PIC.

6 SUMMARY

New Zealand and Pacific coasts are exposed to significant tsunami hazard (GNS, 2005). Hazard from near-source tsunami with little travel time is higher than previously estimated. Unlike earthquakes, where damage is normally confined to a smaller area, tsunami impact long stretches of coastlines, often entire ocean basins. They usually extend inland for a few hundred metres, possibly up to several kilometres in low-lying areas. Primary impacts of tsunamis are based on (drag, lift and inertia) forces which are caused by hydrostatic and hydrodynamic impacts due to the motion of the water. The forces causing primary impact depend on the shape and characteristics of the structure, flow depth and flow characteristics. Secondary impacts of tsunamis are caused in general by dragging of objects, debris flow and driftwood, contaminants together with flowing water. Scour around structure foundations can also cause damage.

This study assessed the critical nearshore tsunami amplitude, momentum and velocity for ports for near-field earthquake scenarios using boundary condition information of maximum tsunami amplitude at the coast and the empirical methods proposed by ASCE 7 (2016).

The interrelation of critical infrastructures can contribute to a system’s vulnerability (by allowing failures to propagate from one network to another, such as in power failures) but perhaps counter-intuitively, also its resilience. Interrelated infrastructure networks can result in redundancies, for example passengers moving from trains to buses in the event of network disruption, or road network disruption could slowed port operation or water trucks using the road network in the event of burst water mains. Understanding how infrastructure networks relate to and depend on one another is important for understanding their vulnerability to natural disasters. Stochastic modelling approaches have been used to quantify how cascading failure modes depend on the interrelatedness of the different critical infrastructure (Bloomfield et al., 2010). Interrelatedness parameters most affected how common large, catastrophic cascading failures were found to be. These are likely to be the hardest to simulate, not least because of the relatively limited set of real-world data to draw on.

The challenges in moving from academic understanding to real-world resilience require cooperation and coordination across multiple sectors, which suggests that governments may be best placed to tackle them. However, government-level interventions risk being ineffective if a best-practice approach is not taken. Herrmann-Lunecke (2015) reviewed the role of public policy and urban planning in tsunami preparedness in Chile before and after the major earthquake and tsunami in 2010, in which more than 500 people lost their lives. Prior to the disaster, little to no policies were in place to mitigate the impact of tsunamis. Since then, policies have been put in place at all levels of government, however their effectiveness has been limited by a lack of consistent standards, a lack of coordination between levels of government, and overlapping (and even competing) regulations and jurisdictions. The tsunami flood maps used in the country prior to 2010 provided relatively accurate predictions of areas affected by the 2010 event, but these hadn't been used to develop policies. In the flurry of work after 2010, more extensive mapping has been carried out, but various parties have produced maps without a standardised method, and the results are not always publicly available. These issues highlight the importance of openness and cooperation when it comes to understanding and planning for the risks of tsunamis.

7 ACKNOWLEDGEMENTS

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