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Contest 2012

Quantifying the landslide-generated tsunami hazard in central New Zealand: A workflow for probabilistic landslide tsunami hazard assessment.

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Quantifying the landslide-generated tsunami hazard in central New Zealand: A workflow for probabilistic landslide tsunami hazard assessment.

2012-NIW-03-NHRP Project Completion Report

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Key message for media:

1. There is a landslide tsunami hazard to Wellington due to the potential for rock and sediment collapsing in the Cook Strait Canyons
2. A magnitude frequency relationship has been developed for submarine landslides in the Cook Strait canyons, and we calculate that specific locations on Wellingtons South Coast can expect waves >5 m about once every 1000-5000 years.
3. This is the first spatial probabilistic landslide tsunami hazard model generated for submarine canyons and shows that canyon bathymetry has an important impact on wave generation

Abstract:

This report covers the 2-year second phase of a 4-year collaborative project focussed on determining the probability of occurrence of landslide-generated tsunami. The objectives of the project are both to bring the methodology up to the standard of that for earthquake generated tsunami, and to assess the hazard to the Wellington region which has been identified as likely to be the most vulnerable area of New Zealand's coastline.

The model workflow for a probabilistic approach to modelling landslide tsunami within submarine canyons is a first in the published literature and defines a methodology that can be applied in other locations. This is important because submarine canyons are one of the few places where steep and high depth range seabed slopes occur in close proximity to the coast.

As part of this project we have tested the effects of bathymetric variation, 2D-3D simplifications and landslide deformation and wave coupling. All of these have

demonstrated important results of interest to the international research community which are in the process of being written up for peer reviewed publications.
The study demonstrates the hazard to Wellington's south coast and particularly to isolated areas such as Turakirae Head is not negligible. The annual probability of exceedance for 5 m tsunami waves around the Wellington south coast was found to range from 0.0012 – 0.0001 or a return period of 800 – 10000 years. Within Wellington Harbour the annual probability of exceedance for 5 m waves is 0.0001 or less. This work needs to be followed up with inundation modelling so the risk can be assessed.

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Introduction / Background

Landslides have been implicated as contributing to approximately 10% of historical tsunami. In certain situations however the impact of landslide tsunami can be very dramatic. The 1958 Lituya Bay tsunami in Alaska remains the largest tsunami wave ever documented, and in 1998 a deep-water landslide in Papua New Guinea triggered a 10-15 m high wave killed more than 2000 people. Coastal areas surrounding the Cook Strait seaway (i.e. Wellington and Marlborough) have a number of factors that make them vulnerable to landslide-generated tsunami hazard: 1) the deep Cook Strait canyons result in steep seafloor slopes in close proximity to the coast, 2) numerous high slip active faults occur near the canyon with three actually crossing the canyon, 3) Wellington's south coast includes areas of high coastal population density and critical infrastructure.

The ultimate goal of this project is to estimate tsunami hazard curves for the Cook Strait region for tsunami caused by submarine landslides. Two main streams of work have combined to produce these tsunami hazard curves. One stream consists of the steps required to establish a probabilistic model of landslide occurrence, these include geotechnical analysis of slope stability, generation of synthetic seismicity catalogues, and determining a magnitude/frequency distribution from mapped landslide data. The other stream consists of physics-based water and landslide modelling, this consists of defining transects across the Cook Strait canyons, modelling of landslide descent and consequent wave generation, and tsunami propagation to the coast.

Two main approaches for calculating the landslide probability curves are being followed. The first is process based: a synthetic catalogue of earthquake-triggered submarine landslides is produced, from which a synthetic catalogue of tsunami heights is generated and interrogated to estimate the hazard curves. The second is empirical: collected data is used to estimate volume-frequency relationships and probabilities of landslide occurrence within the canyon system, which may be directly combined with the tsunami model to produce the hazard curves. This second approach is significantly simpler, but comes at the expense of a more-refined spatial model of landslide occurrence.

Research Aim No. 1: Refinement of a probabilistic model for earthquake-triggered submarine landslide occurrence

Objective Achieved? Yes

Magnitude-frequency curves are the underpinning driver for probabilistic hazard models. In the context of landslides as a tsunami source this requires an understanding of how often different volume landslides occur. We take two approaches to determining the magnitude frequency of landslides within Cook Strait canyons.

Empirical assessment of landslide magnitude frequency from the pre-historic record

A population of 85 landslides has been mapped in the canyons (Micallef et al., 2012). Power law regression provides a representative probability distribution for landslide volume. To generate the magnitude frequency curves shown in Figure 1 we infer a time period over which the landslides have occurred. The physiography and sedimentary dynamics of the Cook Strait seaway have changed significantly in response to glacio-eustatic sealevel rise. During the lowstand period a land bridge between Taranaki and NW South Island reduced the tidal energy transfer between the Tasman Sea and Pacific Ocean that occurs through the strait under present conditions, but maintained strong currents and bed shear stress. This was in place at 20 kyr BP. By 15 kyr BP the land bridge was breached and a period of high sediment flux through the canyon is expected to have resulted in a period of peak canyon modification. By 10 kyr BP sealevel was close to the present day shoreline and canyon dynamics would be similar to that seen today. Dating of 3 landslides indicates ages of approximately 14 kyr BP, 2.5 kyr BP and 1855 AD (Power et al 2011). Based on this information we use a most probable age period for the landslide distribution of 15 kyr. We use a maximum time period of 20 kyr and minimum time period of 10 kyr. From this the magnitude frequency curve in Figure 1 is derived to drive the tsunami hazard model.

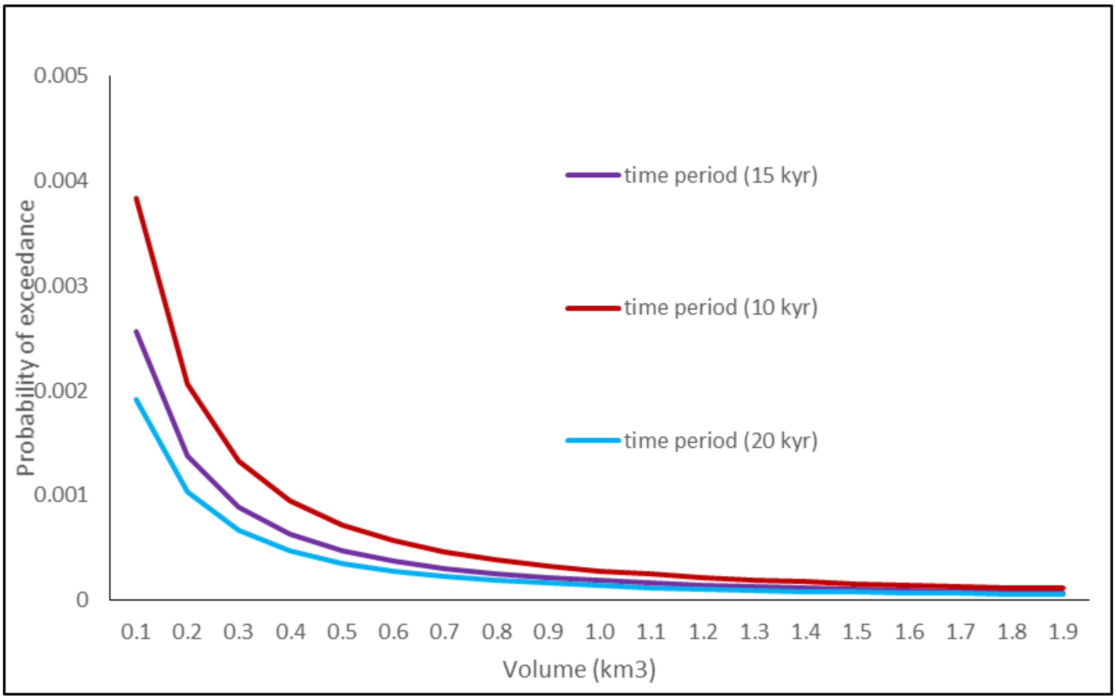

Figure 1: Landslide magnitude frequency curve for Cook Strait canyons

Probability of landslide occurrence from earthquake rupture

In a complimentary approach to determining landslide magnitude frequency we develop a model that is driven by known earthquake sources from the New Zealand National Seismic Hazard Model. The advantage of this model is that it provides information on how the rate of landslide occurrence varies according to location. This builds on work completed in the preceding Natural Hazards Research Platform project (CS-GNS-25, Power et al 2011). This model takes a synthetic earthquake catalogue and uses derived ground shaking levels to model slope stability using a 1-D monte-carlo probabilistic slope stability equation. This work is being written up for publication (Muller et al., in prep) and will be available as a modular add-in to the probabilistic landslide-generated tsunami hazard model.

Landslide occurrence in Cook Strait Canyon floor sediments and the 2013 Cook Strait earthquake sequence.

A study of seafloor sediment instability in the upper Cook Strait Canyon was completed and published this year (Mountjoy et al., 2014). This study used data collected during voyage Tan1103 as part of NHRP project CS-GNS-25 (Power et al., 2011). Material strength data and products derived from the National Seismic Hazard Model were used to determine the long term seismic stability of sediment in Cook Strait Canyon. Evidence for previous landslides in the canyon floor sediments has been modelled for tsunami generation and found to have a negligible effect. The study demonstrated that the process is important for high-stand canyon development, however, with sand and silt sediment is being transported into the canyon by tidal currents to staging points in the upper canyon. Accumulated material then fails during earthquakes every 100-200 years and is transported down canyon, contributing to bed scour of the lower canyon system.
The publication of this paper online coincided with the Cook Strait Earthquake sequence of July 2013. RV Tangaroa was diverted to remap the canyon in the identified area of seafloor instability. This demonstrated that no further failure had occurred, and stability modelling based on expected peak ground accelerations provided by GNS Science seismologists demonstrated the event generated well below the energy required to trigger instability. Press releases associated with this work received wide media coverage and indicated the NHRP as a contributor. The study was principally funded by NIWA Core Funding.

Research Aim No. 2: Improvements to landslide tsunami-generation code

Objective Achieved? Yes

Building on the significant capability development undertaken in CS-GNS-25 we have progressed numerical modelling capability and efficiency in a number of areas:

Tsunami initiation

We divided the Upper Cook Strait Canyon into 176 transects across the canyon. For each of these transects we have created a simplified geometry and modelled the landslide initiation process using a 2D vertical slice Volume of Fluids (VoF) approach where the air, water and landslide are all specified as different fluids. A variety of landslide rheologies were trialled including a Bingham fluid and a dense viscous fluid. We chose to represent the descending landslide as an essentially rigid block by reinitialising the entire landslide velocity to that of its centre of mass at each time step, as this seemed to best represent the initial cohesive nature of the landslide. Once the toe of the block reaches the canyon floor the subsequent evolution of the landslide is modelled as a dense fluid, representing the effective break-up of the block. For each modelled scenario we pick a time after the landslide has reached the bottom of the canyon and before the waves reach the nearest coastline. At this time we take the surface sea level and expand it horizontally from a one-dimensional surface to a two-dimensional surface. This process takes into account the wave length of the wave produced and also the width of the landslide. This two-dimensional surface is used as the initial condition for the tsunami propagation model, which is modelled using the St Venant (Nonlinear Shallow Water) Equations.

Testing the validity of 2D vs 3D model assumption

The 2D vertical slice modelling for landslide initiation is equivalent to assuming that the landslide and the canyon extend indefinitely in the along canyon direction. When the landslide has finite width the height of the wave is decreased. Watts et al. (2005) give a formula relating the 2D wave height with the 3D wave height based on the width of the landslide and the characteristic wavelength of tsunami.

$$W_{2D-3D} = {width}/{(width + \lambda_0)}$$

Where $width$ is the width of the landslide and λ_0 is the characteristic wavelength. Note that as the width goes to infinity this limits to 1. Thus $\eta_{max,3D} = W_{2D-3D} \times \eta_{max,2D}$. So first the η values are adjusted according to this formula.

Deformation process modelling for submarine landslides

In numerical studies, the avalanche type of mass failure presents added complexity and challenge in the simulation of its failure and tsunami generation processes, due to its deformable characteristics in comparison with solid rock slides that have little deformation. We have investigated a two-layer coupled system which simultaneously calculates the evolution of the landslide avalanche and its resulting tsunami. Sub-aerial or submarine landslides are simulated as a viscous fluid or debris avalanche with thickness-integrated mass and momentum conservation equations in a local topography-linked coordinate system. The computed landslide evolution then serves as a transient water layer boundary for the simulation of tsunami generation and evolution.

Using this coupled model, we investigated the failure process of an exceptionally well preserved submarine landslide in the Hikurangi Channel that has both a very well defined source area and deposit. High-resolution multi-beam imaging was used to define the geometry and volume distribution of this submarine slope failure and reconstruct the pre- and post-landslide bathymetry. The modelled deposition agrees well with the observation (Figure 2). The model demonstrated a high efficiency in simulating the coupled evolutions of landslides and tsunami. This is crucial for large scale computations, e.g. in probabilistic hazard analysis which usually requires a few hundreds to thousands of simulations. This study is being written up for publication.

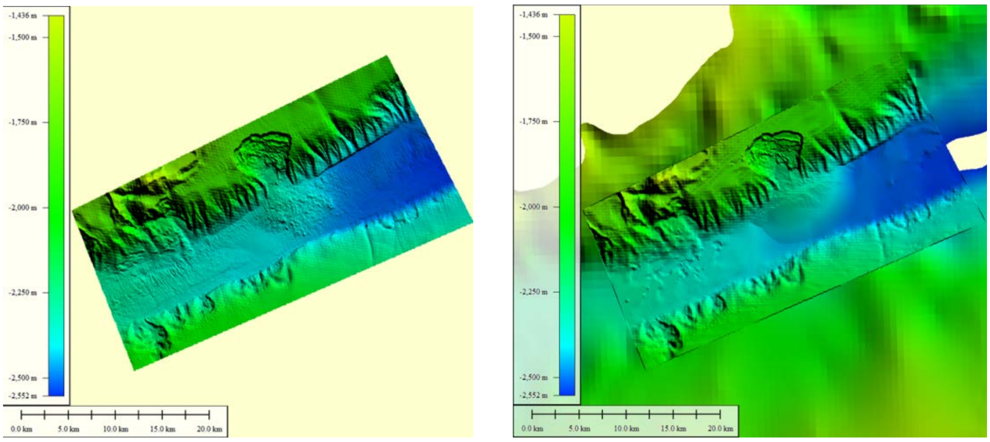

Figure 2: Actual and modelled landslide

Research Aim No. 3: A workflow for quantifying the probabilistic hazard of landslide-generated tsunami at the coast

Objective Achieved? Yes

The fundamental modelling workflow for our probabilistic methodology involves the following steps:

1. To determine the spatial aspects of the source parameters the canyons are divided into appropriately spaced transects.
2. To honor the magnitude regression a range of landslide volumes are modelled on each transect.
3. Transects are used as bathymetric profiles to generate waves within realistic canyon bathymetry.
4. The wave generation model is run in a 3-phase, 2D vertical slice, volume of fluids model, that initially considers the landslide as a rigid block that is able to disintegrate once it reaches the canyon floor.
5. The wave initiated by the 2D vertical slice model is related to a plan-view 2D, depth-integrated model that forms the initial condition for wave propagation.
6. Wave initial conditions for each source volume are propagated to the coast and recorded at points along the 1-m depth contour.

7. The maximum wave height for each source-volume is recorded and is used to derive a curve relating maximum wave height to source volume.
8. The derived magnitude-frequency regression for the landslide-source is then used to derive a probability of exceedance curve for wave heights at each given location.

Model results

The hazard from landslides in the Cook Strait generating tsunami is not negligible.

The annual probability of exceedance for 5 m tsunami waves around the Wellington south coast was found to range from 0.0012 – 0.0001 or a return period of 800 – 10000 years (Figure 3). Within Wellington Harbour the annual probability of exceedance for 5 m waves is 0.0001 or less.
The hazard curves presented in Figure 4 show the highest probabilities occur in close proximity to the canyons (e.g. Turakirae Head) and demonstrate that the Wellington south coast (Wellington – Outer) is also particularly vulnerable to tsunami from landslide-tsunami in the Cook Strait canyons.

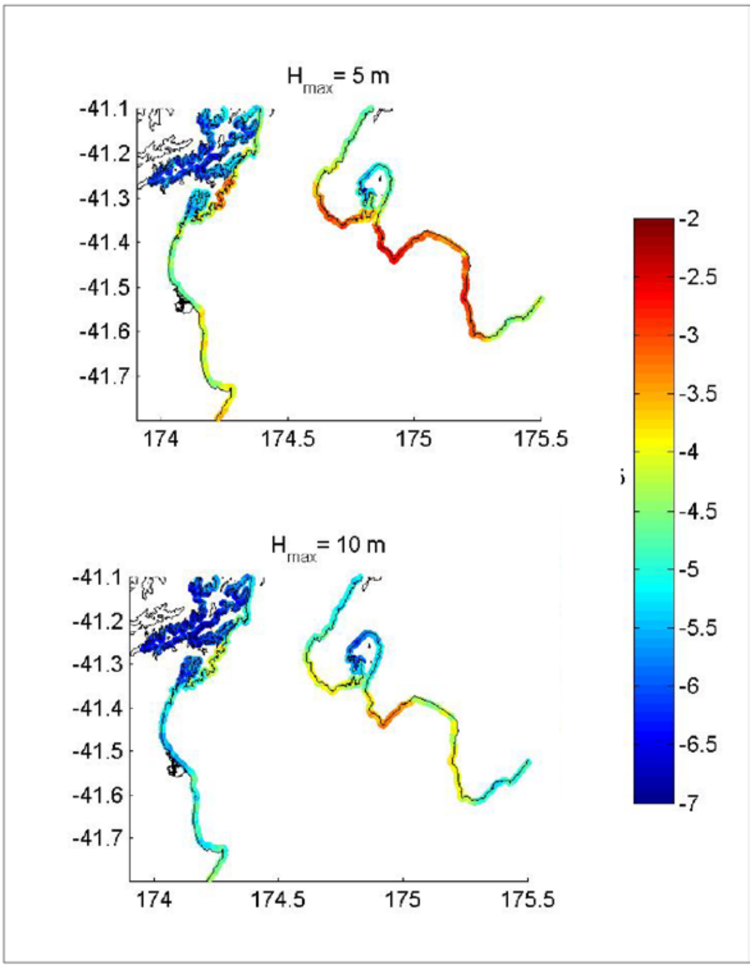

Figure 3: Hazard results as probability of exceedance for 5 m and 10 m wave heights. Scale shows exponential value for annual probability of exceedance (i.e. 10^{-2} – 10^{-7}).

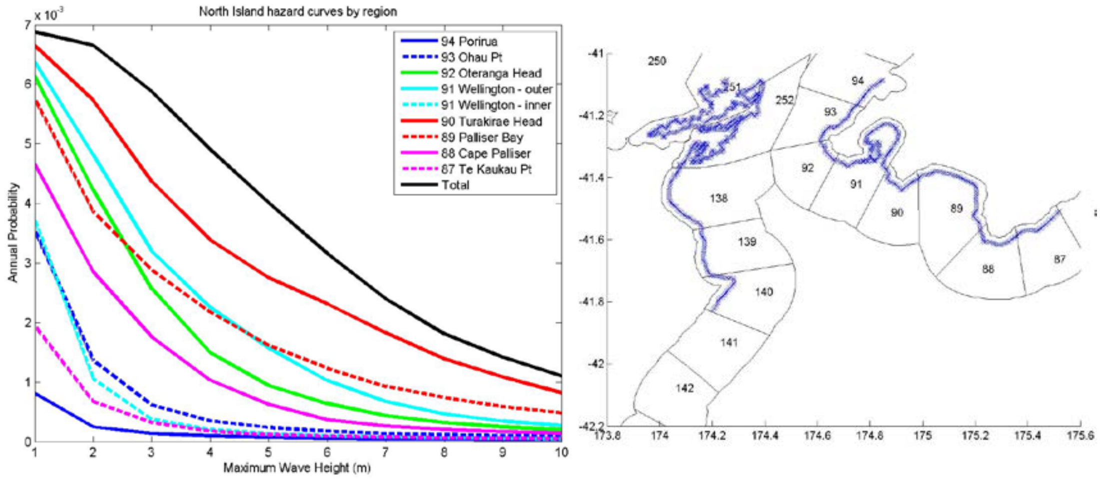

Figure 4: Hazard curves for the domains identified in the 2013 New Zealand Tsunami Hazard Update (shown at right). The curves indicate the probability that the maximum wave height is exceeded somewhere within each domain. The peak wave heights for landslide tsunami are often strongly concentrated within a few kilometres.

Hazard implications

Historical events show that landslide-generated tsunami can be locally catastrophic. This study demonstrates that realistic tsunami wave generation scenarios in the Cook Strait canyons result in large waves at the coast within a short time from initiation.

We can conclude from our modelling that the hazard at any individual site is comparatively low with respect to earthquake-triggered tsunami as the annual probability of damaging waves is significantly lower (with the possible exception of the area around Turakirae Head, where the hazard is comparable at the level of accuracy of our analysis). On top of this, the impact of landslide-generated tsunami waves will be localised and the wavelength will be shorter than that of a tectonic generated tsunami making inundation less severe. However, the very short propagation time and potential for locally large impacts means this tsunami source should not be ignored. And our results show that the populated areas around Wellington's south coast are some of the most vulnerable. It is still necessary to undertake a probabilistic inundation study to enable the risk from landslide tsunami to be quantified and we recommend that this work is undertaken as a follow on to this study.

We have scheduled presentations to the Greater Wellington Regional Council for early 2015 to convey these findings and discuss the work with councillors and civil defence officers.

Overall project conclusions & recommendations:

This collaborative project has brought New Zealand landslide-tsunami modelling capability up to world leading standards. The model workflow developed for a probabilistic approach to modelling landslide tsunami within submarine canyons is a first in the published literature and defines a methodology that can be applied in other locations.

The study demonstrates the hazard to Wellington's south coast and particularly to isolated areas such as Turakirae Head is not negligible, and this work needs to be followed up with inundation modelling so the risk can be assessed.

Testing the effects of bathymetric variation, 2D-3D simplifications and landslide deformation and wave coupling have all demonstrated important results of interest to the international research community.

Refining the model in terms of spatial and temporal occurrence of landslides remains an ongoing challenge that is not unique to this project.

We recommend that further work be undertaken to complete:

1. A probabilistic inundation model so that the risk posed by tsunami to Wellington coastal populations can be determined
2. A combined tectonic and landslide source tsunami model through to inundation.

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Outputs from this project:

Manuscripts

Wang, X., Mountjoy, J., Power, W., Lane, E. and Mueller, C. in prep. Revealing the Failure Process of a Submarine Landslide near Cook Strait and Its Associated Tsunami. Submarine Mass Movements and Their Consequences. G. Lamarche, J. Mountjoy et al (eds), Springer Netherlands.

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