The hazard and risk of tsunami inundation due to submarine-landslide-generated tsunamis in Cook Strait Canyon

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1. Introduction
Wellington is a tectonically active area with a high earthquake hazard. Many of the nearby faults extend under Cook Strait leading to the possibility of an earthquake triggering a tsunami. The last major earthquake in Wellington (1855 Mw 8.2-8.4 on the Wairarapa fault) generated a tsunami that impacted areas from Waikawa Beach in the north to Clarence in the south; caused over 10 m runup height in Palliser Bay and is reported to have over-swept the area that is now Lyall Bay and Kilbirnie with waves approaching from both sides of the Rongotai Isthmus [3] (See Figure 1 for locations). However, in addition to the hazard of coseismic tsunamis (tsunamis caused by earthquakes) there is the possibility that submarine landslides into Cook Strait Canyon could also cause tsunamis. Not only could these augment a coseismic tsunami but they might be triggered by an earthquake on land or a strike-slip earthquake that would not otherwise generate a tsunami.

Worldwide, it is estimated that around 7% of tsunamis involve submarine landslides [4]. Submarine landslides occur over far smaller areas than large earthquakes so the effects of the tsunamis they generate are more localised in extent. However a landslide may extend from the continental shelf down to the canyon bottom – a distance of several hundred metres or more – and so those localised effects can be very large. For example, in Papua New Guinea in 1998 an earthquake triggered a submarine landslide. The resulting tsunami caused waves over 10 m high in Sissano Lagoon and killed over 2,200 people [13]. The Cook Strait Canyon is a submarine canyon that feeds into the Hikurangi trough. At the head of the canyon it splits into three parts, Cook Strait, Nicholson and Wairarapa Canyons. Nicholson Canyon lies within 10 km of Wellington city (Figure 2). The canyon walls drop from the continental shelf at around 100 m depth to several hundred to a thousand metres of water depth. Although the rapid scouring caused by tidal currents through Cook Strait flushes debris out of the canyons, their sides are marked by numerous landslide scars. Studies of these scars estimate realistic landslide volumes up to 1-2 km³ [7].

Given the existence of these scars and the proximity of Wellington city, submarine-landslide-generated tsunamis were identified (in [1]) as being an area of tsunami research that required more work. Subsequently two projects funded through the New Zealand Natural Hazards Research Platform have studied this issue, culminating in a probabilistic tsunami hazard assessment (PTHA) of wave heights at coast for the Cook Strait region [8]. This paper extends on those studies.

Figure 1 Map of Wellington region showing locations mentioned in text. Bounding box of the inundation study is shown in red.

Current tsunami risk reduction efforts in Wellington focus on mapping coseismic tsunami inundation zones, based on 'rule of thumb' calculations, and raising community awareness of these zones [5].
These tsunami inundation zones only represent a 'worst case scenario.' However understanding the full range of potential tsunami risk is vital for decision making [6]. PTHA allows planners and hazard managers to understand the hazard posed by submarine-landslide-generated tsunamis and how it compares with other hazards such as earthquakes and coseismic tsunamis. Ideally, a hazard manager would have access to not only wave heights at coast but full inundation maps for different probability levels. However, especially in the case of submarine-landslide-generated tsunamis, the effects that source location have on final inundation make this difficult.

Figure 2 Map showing the Cook Strait Canyon and its proximity to Wellington. Inset shows position in relation to New Zealand. Blue colours are below sea level, green colours are above. Landslide scars can be seen on the canyon walls.

The topography of Cook Strait affects the inundation caused by submarine-landslide-generated tsunamis. The Cook Strait Canyon is steep sided with the depth dropping from around 100 m to up to 1 km over a few kilometres. Differences in canyon depth, steepness of failure- and far-slopes and canyon width in different locations all affect the tsunami generated. With land on both sides of Cook Strait there is potential of inundation from both the forward-propagating wave and the reverse-wave generated by the deceleration of the landslide at the bottom of the canyon. The direction of the landslide also strongly affects the inundation.

This work builds on the wave-height-at-coast PTHA results by using inundation results from the relatively coarse (100m) modelling that was undertaken in the original project [8]. We show that, although these results are too coarse to use directly to calculate losses and risks, we can use them to get indicative results on expected inundation and exposure levels for different return periods. We suggest that this method could be used to identify scenarios at specific return levels and assist with risk assessments.

2. Methodology.

The impacts of submarine landslide generated tsunamis, although potentially extreme, generally occur over a localised area (tens of kilometres). Even within an area the size of Cook Strait the effects of tsunami inundation are very much dependent on the location of the source. Figure 3 shows examples of maximum wave heights for 4 tsunamis generated by 1 km$^3$ landslides in different locations in the canyon. We need to understand how this variability affects the impact of landslide-generated tsunamis.

The modelling work, as reported in [8], fully explored the effects of submarine-landslide-generated tsunamis in Cook Strait Canyon. Here we outline the process to provide background to this work. To this end, Cook Strait Canyon was divided into cross-sections approximately 1 km apart, 176 cross-sections in total. For each cross-section, we developed a representative two-dimensional slice with simplified bathymetry. Three different volumes of landslide (0.1, 0.3 and 1 km$^3$ respectively) were modelled on each cross-section. These results were used as initial conditions for tsunami inundation modelling. Because this meant simulating 528 scenarios, the modelling was done at relatively low (100m) resolution (for inundation modelling at least). The original report [8] only reports wave heights at the coast. However, the hydrodynamic model used included topography around Wellington that derived from LiDAR data and the Gerris solver includes inundation [9,10]. Thus, at the 100m resolution level, inundation was modelled. Although this is coarse for risk assessment at an individual level, we are still able to use the results to understand the nature of inundation caused by landslide-generated tsunamis. We can also use it as a guide for choosing scenarios for higher resolution inundation modelling.

The most vulnerable region along the exposed coastline is Wellington city, the capital of New Zealand, home to 11% of the population and over 52,000 businesses [2]. Therefore, although the modelling includes all of greater Cook Strait this study focuses on inundation around Wellington.

For each scenario modelled, the inundation that occurs within a box bounded by 174.76 and 175 degrees east, and by 41.4 and 41.2 degrees south (see Figure 1), was stored. We use these results to calculate statistics on overall inundation in this region. The remaining results are all based on this region.

Assuming that landslides are equally probable over the entire canyon, we calculate the probability of inundation of any given location in the region, resulting from a landslide of a certain volume occurring somewhere in Cook Strait Canyon.
also calculate the expected and maximum inundation depth at each point given a landslide of a certain volume. We sum the total inundated area within the region for each event. These are plotted at the landslide source locations to identify which source locations pose the greatest hazard to the Wellington region.

The results are collated to give cumulative frequency graphs for inundated areas over given thresholds. Using the fact that a landslide with zero volume will cause no inundation with probability 1 and interpolating between the cumulative frequency functions, a relationship between volume, \( V \), area, \( A \), and probability, \( P \), can be expressed as \( P(A \geq X | V=Y) \), i.e. the probability that an area greater than size \( X \) \( \text{km}^2 \) is inundated given that a landslide of volume \( Y \) \( \text{km}^3 \) occurs somewhere in Cook Strait.

\[
P(A \geq X | V=Y) = p(X,Y)
\]  

In [8], a simple empirical magnitude-frequency relationship was developed for submarine landslides in Cook Strait Canyon using the mapped landslide scars and an estimate of their emplacement time, i.e.

\[
P_{\text{annual}}(V \geq Y) = g(Y)
\]  

Bringing together Equations (1) and (2) and integrating all the possible volumes, calculates the expected inundation area for a given annual probability:

\[
P_{\text{annual}}(A \geq X) = \int_{0}^{V_{\text{max}}} p(X,Y) g(Y) dy
\] 

Thus, the expected maximum area of inundation for a given return period can be estimated. This can be calculated not just for inundation but also for inundation over a given threshold (say 0.5 m). Because of the coarseness of the modelling in this instance, the numbers are not exact. However the indicative results and the ranking of different scenarios in terms of their impacts are still relevant.

While the size of the area inundated is a useful tool for gauging the impact of a tsunami, the actual impact on the local population could vary markedly depending on how the area is developed (say residential or industrial). To move from calculating tsunami hazard to determining the risk to life and property the RiskScape tool [12] is used to assess potential exposure of different assets. With high resolution output from a tsunami inundation model we could map the inundated area, for each building or other asset that is exposed and use vulnerability models to calculate building damage and likely injuries or deaths to people in them. By summing these damages, the RiskScape tool can estimate the tsunami’s total cost in measures such as monetary cost or people injured and killed.

Because of the coarseness of the tsunami inundation modelling, in this paper we do not take full advantage of RiskScape to quantify potential building and human losses. Rather we report on the assets exposed; in particular the probable exposure of buildings and people taking into account all 528 scenarios. For people, we consider both day- and night-time scenarios. With these we can develop an equation analogous to Equation (1) but for the asset exposure level rather than the size of area inundated. By following the same process as above, this equation is integrated with Equation (2) to give the expected asset exposure level due to submarine-landslide-generated tsunamis at different average return intervals (i.e. an equation analogous to Equation (3)). Thus if we are most interested in people or buildings exposed (say) we can calculate the expected numbers of people (or buildings) exposed as a function of average recurrence interval and use that as our measure for determining scenarios for finer resolution modelling.

3. Results

Figure 3 shows examples of the maximum wave heights for four different landslides of volume 1 \( \text{km}^3 \) originating in different regions in the canyon, with different underlying bathymetry and aspect. These examples illustrate how sensitive the inundation is to the source parameters and why it is necessary to model each scenario individually. This also complicates the process of choosing a representative event because different events may be equally ‘bad’ (by some measure) but may affect different areas.

Inundation in the Wellington region is most likely along the exposed southern outer coast. Figure 4 shows the probability of inundation, given a landslide of the three volumes (0.1, 0.3 and 1 \( \text{km}^3 \); top left, top right and bottom left respectively) for the Lyall Bay to Kilbirnie region, including Miramar. This encompasses the low lying land between...
Lyall and Evans Bays that connects Miramar Peninsula to the rest of Wellington. Wellington airport lies in this region as well as a combination of residential and industrial properties.

Figure 4 Top left, top right and bottom left show the probability of inundation for Lyall Bay through to Rongotai and Miramar given landslide volumes of 0.1, 0.3 and 1 km$^3$ respectively, occurring somewhere in Cook Strait. White areas are not inundated in any of the scenarios. Dark blue indicates low probability of inundation through to red being high probability. Bottom right shows maximum inundation depth for all the scenarios for landslides with volume 1 km$^3$. The colour scale runs from 0 to 10 m.

For landslides of volume 0.1 km$^3$ most of the inundation is confined to the coastal strip – beaches and rocky outcroppings. In some cases, however the inundation reaches into Lyall Bay and Rongotai. It is possible, but unlikely, that the lowest lying part of the Wellington Airport runway will be inundated.

For landslides of volume 0.3 km$^3$ it is very likely that the coastal part of Lyall Bay and Rongotai and the coastal road are inundated. There is about a 40% chance that the inundation will extend inland covering about half the isthmus and including the lower part of the airport runway. There is a small chance that it will inundate most of the southern part of the runway and extend inland toward Kilbirnie and Miramar.

For a landslide of volume 1 km$^3$ the southern part of Lyall Bay including the lowest lying part of the runway will almost certainly be inundated. There is around a 40% chance that most of Rongotai, Kilbirnie and the southern part of the runway are all inundated. There is a small chance that all of the low lying land in Miramar is inundated. Figure 4 (bottom right) shows the maximum possible inundation depth for all the scenarios. In general the areas that are more likely to be inundated are also the areas that are inundated more deeply but this is not always the case. Lower lying areas of Miramar may be inundated to deeper levels than the more frequently inundated areas closer to the coast.

Figure 5 shows the effects source location and characteristics have on inundation in the Wellington region. The size of the inundated area is plotted at the source region of the landslide for landslides of 0.1 (top) and 1 (bottom) km$^3$ volume. For smaller landslides, proximity appears to be the most important factor in determining the effect of the resulting tsunami. All the landslides pointing either towards or away from Wellington in the Nicholson Canyon cause significant inundation given their size. Only the nearby landslides that run parallel with the coast do not cause much inundation. After that landslides in the southern arm of Cook Strait Canyon that point towards the harbour opening and landslides on the eastern side of Wairarapa Canyon that get funnelled in towards Wellington cause the most damage. For bigger landslides proximity is not nearly as important. The greatest inundations are caused by tsunamis which either travel directly towards Wellington Harbour or which are guided in that direction by the underlying bathymetry.
Figure 6 shows the cumulative frequency graphs for size of area inundated for the three volumes and for inundation over 0, 1 and 2 m. For simple inundation the graphs for the three volumes are very similar but the scale is just increased for larger volume landslides. For all three landslide volumes there is a chance that negligible inundation will occur. The maximum inundation expected from a tsunami generated by a landslide of volume 0.1 km$^2$ is around 2.5 km$^2$. In the case of a landslide of volume 1 km$^2$, however, it could cause up to around 16 km$^2$ of inundation. As we look at higher levels of inundation, however, some differences appear. For 0.1 km$^2$ landslides there is around a 35% chance that there will be no inundation greater than 2 m deep.

Figure 6 Cumulative frequency graphs for area of inundation in Wellington Harbour for three volumes of landslide. X-axis is size of area in km$^2$ and Y-axis is probability of inundation less than that amount. Rows from top to bottom are for tsunamis caused by landslides of volume 0.1, 0.3 and 1 km$^2$ respectively. Columns from left to right are total inundated area, then inundation over 1 and 2 metres respectively. Note that even large landslides may not cause much inundation in Wellington Harbour. In these cases it is likely that the main force of the tsunami is directed towards another part of the coast.

The left column of Figure 6 is the basis for Equation (1). By bringing in the probabilistic information of landslide occurrence (Equation (2)) we get Equation (3) which is plotted in Figure 7 (top left). Note, however, that annual probability has been inverted on the y-axis to give average recurrence interval. It is interesting to note that although submarine-landslide-generated tsunamis are expected, on average, approximately every 140 years it is only submarine-landslide-generated tsunamis of return periods of about 200 year or higher that are expected to cause any appreciable inundation. The expected inundation increases quickly at first to around 0.25 km$^2$ before falling away exponentially for higher levels of inundation. The 1:500 year ARI inundation is around 1 km$^2$. The graph shows that although it is possible that a submarine-landslide-generated tsunami could cause inundation over an area up to 16 km$^2$, inundation to this extent is very unlikely (ARI 1:1,000,000 years for inundation over 14 km$^2$).

We can compare the size of area inundated in Figure 7 (top left) with the number of buildings inundated in Figure 7 (top right). As with the size of the area inundated we are not differentiating in this figure between buildings that are only slightly inundated and buildings that face extreme inundation. We could use the same method to calculate buildings exposed to a given threshold of inundation and, as mentioned in Section 2, if we were using higher resolution modelling we could not only measure exposure but calculate expected individual damage states and estimate replacement costs. The two graphs look very similar which suggests that the buildings are expected to be fairly evenly distributed over the inundated area with an average density of around 1,000 buildings per square kilometre.

The number of people exposed to the tsunami is shown in Figure 7, bottom left and right for day-time and night-time scenarios respectively. These figures assume no evacuation, which is relatively reasonable given that the first tsunami wave could hit the shore within 5-10 minutes of the landslide occurring. So, even if the landslide was triggered by an earthquake which acted as a natural warning, there would be very little time in which to react and evacuate. The first thing to note is that the scale on the day-time plot is around twice that of the night time plot indicating higher occupancy in day-time (commercial, industrial and educational rather than residential). Also the day-time scenario shows two rapid increases in exposure rather than just the one as is seen in all the other graphs. The first occurs at similar ARI to the other graphs but the second is for around the 1:300 year submarine-landslide-generated tsunami. This most likely represents tsunami inundating areas expected to have high occupancy during the day-time. The night-time scenario shows a slightly faster increase in exposure at around the same ARI but nowhere near as steep as the day-time scenario.

4. Discussion

This work shows that tsunamis generated from landslides in Cook Strait Canyon do pose a tangible threat to Wellington City. This study also begins to quantify this threat in terms of exposure of people and property. Although the current modelling is at a coarse resolution for inundation modelling and so cannot be used for the detailed risk modelling possible through the RiskScape tool, it does outline how we could make more definite risk calculations using these results. From the magnitude-frequency graph of whichever hazard metric you wish to use (e.g. size of area inundated, number of buildings exposed, number of people...
exposed), take the hazard level that represent return periods of interest e.g. 1,000, 2,500 and 10,000 years. Scenarios that represent that level of hazard can be found from the coarse modelling. These scenarios can then be simulated at high resolution and entered into RiskScape to provide more accurate estimates of what level of risk might be expected.

There are still many unknowns in the area of submarine landslides and so there are a lot of assumptions made in developing these results. As such results should be thought of as preliminary and more of an order of magnitude assessment. However this work shows a methodology that can be used to develop probabilistic information about submarine landslides.

Figure 7 Average recurrence interval (ARI) in years as a function of (Top left) Size of area inundated (kilometres squared). (Top right) Number of buildings exposed (thousands). (Bottom) number of people exposed (thousands), day-time (left) and night-time (right) scenarios. Note that although a submarine-landslide-generated tsunami can be expected on average approximately every 140 years or so it is only tsunamis with return periods of around 200 years or higher that the risk starts to become appreciable.

Here we discuss some of the assumptions and uncertainties implicit in this work. The landslide probability estimate is based on assumptions about the timeframe over which the identified landslides have occurred, and that they occur with equal probability over the entire canyon. The validity of these assumptions is not certain, however changes could quickly be accommodated within this framework. While a best guess of 15,000 years was used as the timeframe, it could range from 10,000 to 20,000. This would just shift the probabilities up or down the ARI scale. Spatial variability in landslide probability could have a more dramatic effect for better or worse depending on whether source locations that Wellington is susceptible to become more or less likely. It would just be a matter of weighting these results differently to take this into account.

Details of the landslide modelling and the resolution of the grid also lead to uncertainty. With increased computational power it may be possible in the future to model scenarios more exactly and at higher resolution but there will always be epistemic uncertainty about the nature of the landslide that occurs. Other unknowns such as tidal cycle and whether the landslide generated tsunami occurs in addition to a coseismic tsunami also increase the uncertainty. An area for future research involves attempting to quantify all these uncertainties to get some form of error bars on our results. A method such as the PTHA done in [11] would be one way of accounting for this.

In the case of a combined coseismic and landslide generated tsunami it is not yet obvious how to combine results from this and whether these would need to be calculated simultaneously. This is also an area for future research.

5. Conclusions

Even though the tsunami scenarios only model inundation at 100m resolution, they use accurate underlying topographical information and are modelled using the full 2D hydrodynamic equations. As such they give self-consistent, if coarse, information on the relative impacts of the different scenarios on the Wellington region. This paper shows that we can use these scenarios to gain an overall picture of the impacts according to a metric that suits our needs. They can also guide us in selecting specific scenarios to model at higher resolution for full risk assessment.

6. References


Hazard and risk of submarine-landslide-generated tsunamis in the Strait, New Zealand: 201-212. 10.1007/978-94-007-2162-3_18


