A pilot study on effectiveness of flow depth as sole intensity measure of tsunami damage potential

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ABSTRACT

Current practices have commonly used tsunami flow depth as the sole hazard Intensity Measure (IM) in fragility functions underpinning tsunami damage, loss and risk assessments. Tsunami flow depth is often obtained from tsunami inundation modelling with Equivalent Surface Roughness (ESR) assumption that removes ground surface features such as buildings and applies equivalent roughness values in a bottom friction model. This approach is potentially error-prone. As a static measure, flow depth alone can be a biased IM of tsunami damage potential. It does not completely account for flow dynamics and kinetic energy which contribute directly to the severity of tsunami impact. In this study, we evaluate the effectiveness of flow depth as the sole IM of tsunami damage potentials, using high-resolution comparative simulations at the Wellington Central Business District (CBD) in New Zealand. Our results show that firstly explicit CBD buildings would significantly alter tsunami flow patterns, resulting in possibly significant uncertainties and inaccuracies, up to 40-60%, in flow depth estimates with the ESR modelling in many areas of the Wellington CBD. Additionally, flow depth shows large dependencies on topography features and its spatial distribution does not correlate with that of momentum flux, a direct measure of tsunami impact. In contrast, momentum flux shows continuous attenuation from coast to further inland, consistent with observations of building damage in past tsunami events. We conclude that tsunami flow depth alone may not be an effective hazard IM of tsunami damage potential, especially in built-up areas with complex topography.

1 INTRODUCTION

In current practice of tsunami hazard and risk assessments, tsunami flow depth, i.e. inundation depth, has been widely used as a key, often a sole, tsunami hazard Intensity Measure (IM) in fragility functions underpinning tsunami damage, loss and risk assessments (De Risi et al. 2017). This type of functions relates tsunami flow depth to a level of building damage or loss (Suppasri et al. 2012; Horspool et al. 2015). And the flow depth values used in these assessments have been commonly obtained through the Equivalent Surface Roughness (ESR) approach tsunami simulations. In the ESR approach, ground surface features, such as buildings and vegetation, are usually removed and replaced with equivalent roughness values, e.g., Manning's n, in a bottom friction model to approximate their retarding effects on incoming tsunami flows in tsunami simulations (Wang and Power 2011).

However, as a static indicator, maximum flow depth alone can be a biased measure of damage potential because flow dynamics and kinetic energy, which contribute directly to the severity of tsunami impact, are not completely accounted for, especially over complex ground topography (Arimitsu et al., 2013; Song et al. 2018). Momentum flux instead which has a unit of force per metre, is a better measure to reflect potential tsunami impact as it combines the effect of flow depth and velocity, and thus directly correlates tsunami damage potential of buildings (Wang and Liu, 2007; Yeh et al. 2014; Chock 2016; Charvet et al. 2017).

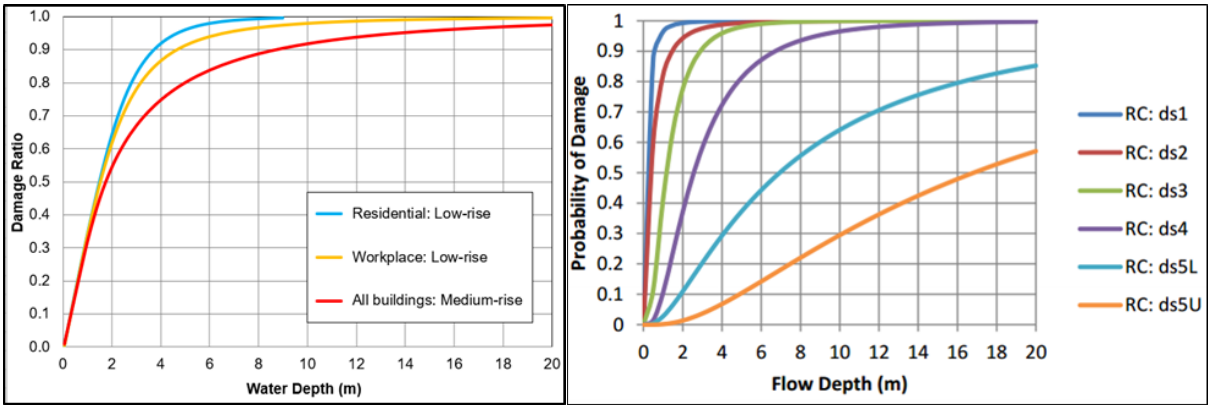

Figure 1: Fragility functions that relate a level of damage to tsunami flow depth for different types of buildings. Left Panel: for New Zealand buildings (Horspool et al 2015); Right Panel: for reinforced concrete (RC) buildings in Japan (Suppasri et al. 2012)

Additionally, small scale experimental and numerical studies indicate that the existence of vegetation, buildings and other macro ground surface features in the path of tsunami flow can reduce inundation extent, and significantly alter flow pattern, timing of inundation, and the distribution of maximum flow depth (Hiraishi and Yasuda 2006; Augustin et al., 2009; Goseberg and Schlurmann, 2011; Park et al., 2013). This has a particularly important effect in urban areas where buildings tend to be solidly built and unlikely completely collapse in tsunami events. In these areas, flow depth can significantly increase in front of the buildings and decrease on their lee-side, as reported in the 2011 Tohoku tsunami in Japan (Fraser et al., 2013). In built-up areas, the removal of ground surface buildings and structures in the ESR approach modelling inevitably introduces inaccuracies in the estimate of flow depth, and consequently in the estimtes of tsunami damage or losses.

In this pilot study, we seek to improve our understanding on the effectiveness of the current practice by investigating two areas that may introduce inaccuracies in the estimate of building damage potentials: (1) the use of flow depth as the key/sole hazard IM in the fragility functions, and (2) the estimate of flow depth using the ESR approach modelling.

2 METHODOLOGY

2.1 Study Site and Tsunami Source

The Central Business District (CBD) of Wellington City was selected as our study site in this investigation where both high-resolution LiDAR data and building information, including building footprints and heights, are available from past studies (Wang et al. 2017a). The Wellington CBD sits inside the Wellington Harbour in the southern end of North Island, New Zealand. It is relatively sheltered from direct impact of tsunami from the open sea, with flat topography in the waterfront area and gradually rises further inland before merging to steep slope and hilly areas. Most buildings at the Wellington CBD are high-rise, reinforced concrete structures with relatively large gaps between the buildings (Figure 1a).

Wellington sits on top of the Hikurangi subduction interface where the Pacific plate is subducting beneath the Australia plate at a rate of 20-30 mm per year (Wallace et al., 2012) which is likely the source of largest tsunamis in this region. In this study, an Mw8.9 Hikurangi earthquake scenario (Cousins et al. 2007) was adopted as the source for tsunami simulations. This source scenario assumes that a rupture on the plate interface under the southern North Island extends along the interface into Cook Strait, with approximately 12–18 m of dip-slip motion on the plate interface in the Cook Strait region. Figure 1b shows the spatial distribution of vertical co-seismic displacements of this earthquake scenario, computed with the method of Okada (1985), which was used as the source of tsunami simulations.

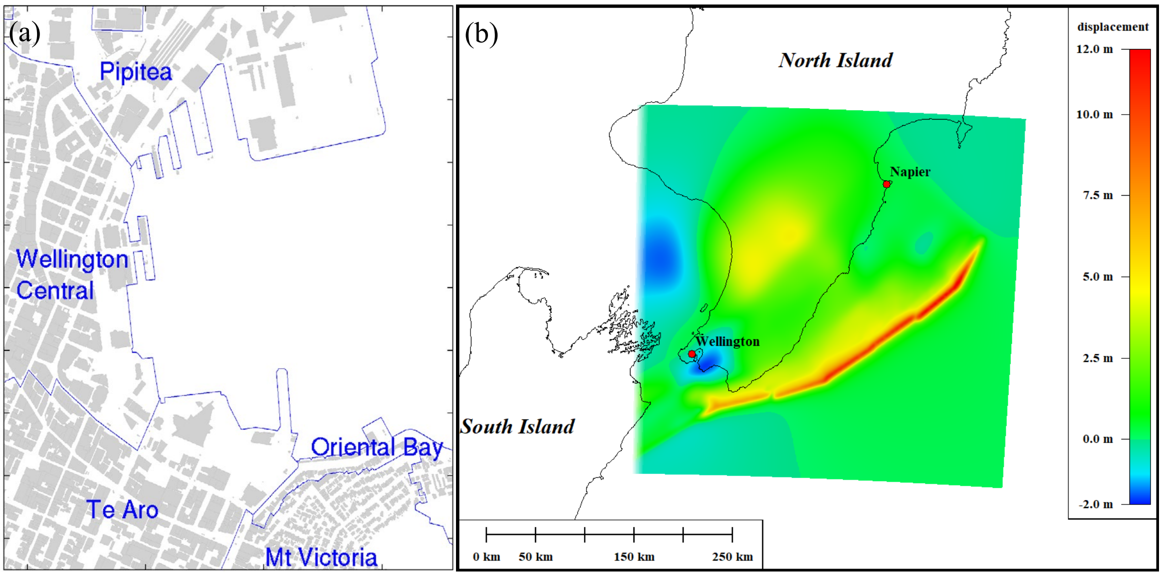

Figure 2: (a): Wellington CBD suburbs with building footprints shaded as grey colour filled polygons; (b): Co-seismic vertical displacement of a Mw8.9 southern Hikurangi earthquake scenario.

2.2 Numerical Modelling

We used a well-established tsunami simulation model - COMCOT (Cornell Multi-grid Coupled Tsunami) to simulate the tsunami generation, propagation, coastal run-up and dynamic onshore flooding processes in the coastal areas of the Wellington CBD to obtain key tsunami hazard IMs, e.g. tsunami flow depth, flow velocity and tsunami elevation.

COMCOT was originally developed by the wave research group at Cornell University, USA (Liu et al. 1998; Wang 2008). It has subsequently been under continued development at GNS Science, New Zealand. This numerical model can simulate the entire duration of a tsunami, including its generation by earthquakes and landslides, transoceanic propagation, coastal run-up and inundation (Wang and Power 2011). It has been further developed to handle potential wave breakings with an ad-hoc algorithm (Kennedy et al. 2000; Lynett

2002) and the explicit inclusion of buildings as solid blocks on top of the bare ground DEM data allowing various permeabilities and tsunami overtopping (Wang et al. 2017a).

Two comparative simulations were performed to evaluate the effects of explicit inclusion of buildings in the study site, one used Explicitly Representing Building (ERB) approach that explicitly included individual buildings as solid blocks with zero permeability, constructed with building footprints and heights; the other used the ESR approach that all the buildings were removed and replaced with equivalent roughness values in a friction model to account for their effects on tsunami flow. Both simulations used the same model settings except for the different treatments of buildings.

In both ERB and ESR approach simulations, two-way nested grids (Wang and Power 2011) were implemented at cascading grid resolutions, telescoping from 1.0 arc-minute (about 1.3 km at the latitude of Wellington) in the open sea for the tsunami propagation calculation to about 1.0 m at the Wellington CBD for the calculation of highly detailed tsunami inundation processes. In the ERB approach, should incoming tsunami waves be high enough, overtopping of a building is allowed and simulated in the modelling. It was further assumed that these buildings would survive shaking from the earthquake and remain standing, non-deformable, and impermeable, during the subsequent tsunami impact. Tsunami propagation and inundation processes were modelled for 5 hours to ensure that maxima of key hazard parameters are reached.

For areas with different types of land covers, we used different roughness values, i.e., coefficient n in Manning's formula, as proposed by Wang et al. (2017a) in Table 1. In the ESR approach simulation, a constant Manning's n = 0.060 was applied to the entire CBD built-up area to model the retarding effect of buildings on tsunami inundation in the ESR approach. n = 0.025 was used in large open areas like parks and bare land and was also used for open space areas between the buildings, e.g. streets.

As demonstrated in Wang et al (2017a), using these roughness values, the ESR and the ERB approach modelling gives very similar tsunami inundation extents in the Wellington City area.

Table 1: Roughness values for different land-cover groups for tsunami inundation modelling in this study.

Land-cover group	**Manning's n***
Built-up area (e.g. urban/residential/industrial)	0.060
Tall vegetation (e.g. forest)	0.040
Scrub (e.g., low trees/bushes)	0.040
Low vegetation (e.g., grass)	0.030
Urban open area (e.g., paved/smoothed)	0.025
Bare land (e.g., farm land)	0.025
Water area (e.g., riverbed/seabed)	0.011

For both simulations, maximum momentum flux, F, was also calculated with the following equation

$$F = \rho|h\vec{u}|\vec{u}, \qquad (1)$$

where h represents tsunami flow depth, $\vec{u} = (u, v)$ denotes tsunami flow velocity, (u, v) are velocity components, and ρ is the average density of seawater at the surface, $\rho = 1025 kg \cdot m^{-3}$.

Momentum flux, with a SI unit $kg \cdot s^{-2}$ (i.e. force per metre width in tsunami flow), has been widely used in the calculation of tsunami forces on structures, such as drag force and impulsive force (Wang and Liu 2007; Yeh et al. 2014; Tanaka et al. 2015), and design tsunami loads for tsunami-resistant structures (Chock 2016), by applying appropriate multipliers, i.e. coefficients. Maximum momentum flux is thus proportional to the maximum tsunami force a structure would experience per metre width in tsunami flow in a tsunami event.

In the numerical simulations, both maximum flow depth and maximum momentum flux have been calculated with the ESR approach and the ERB approach, respectively.

3 RESULTS AND DISCUSSIONS

In this study, we adopt maximum momentum flux, proportional to tsunami force that a structure would receive per metre width in tsunami flow, as an unbiased direct measure of building damage potential, and use it to evaluate the effectiveness of using flow depth as the key tsunami hazard IM in the fragility functions for the estimate of building damage potential in the current practice.

We make a side-by-side comparison of the spatial distributions between maximum momentum flux and maximum flow depth, obtained from the ESR approach that has been commonly used in the current practice, to identify the disparities between the two parameters.

As shown in Figure 3, it is obvious that momentum flux shows an overall pattern of continuous attenuation in its magnitude from the coast to further inland area, although there are some variations along the coastal stretch, possibly due to the variations in complex coastal topographic/bathymetric settings. This attenuation pattern is consistent with the spatial distributions of the severities of building damage observed in the past tsunami events (Fraser et al. 2013).

In contrast, the spatial distribution of maximum flow depth seems more controlled by topographic settings and does not correlate with the spatial distribution of maximum momentum flux at the Wellington CBD, as evidenced by the areas outlined with black boxes in Figure 3. According to the fragility functions shown in Figure 1, the larger flow depth further inland in the black box areas in the left panels of Figure 3 means more damage to buildings further inland than near waterfront. This contradicts what were observed in the past tsunami events.

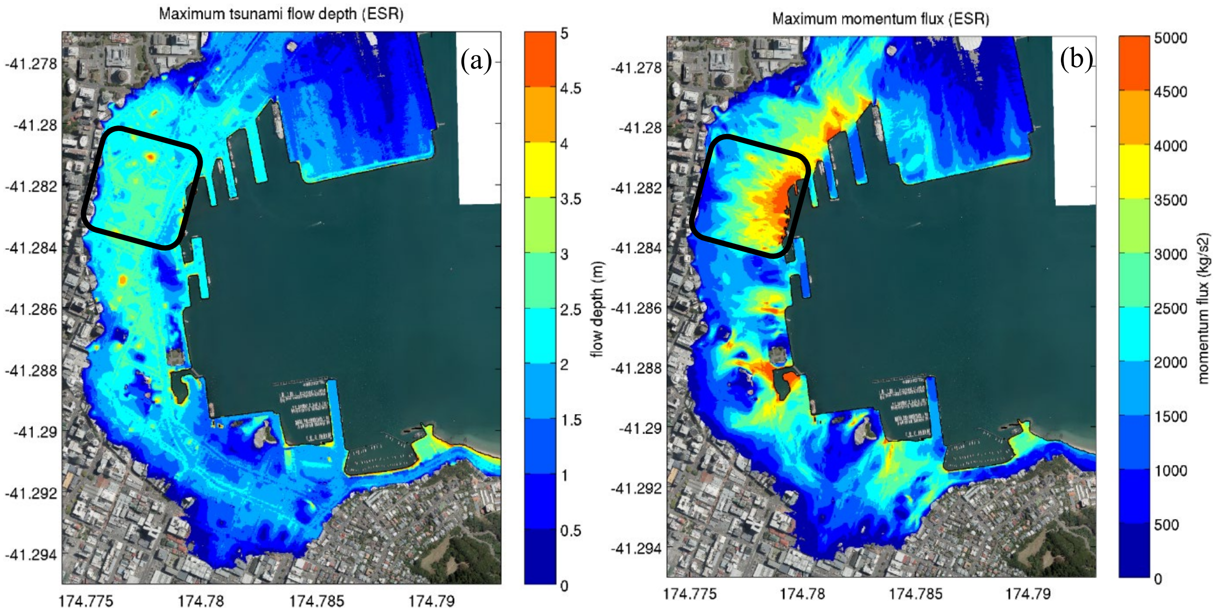

Figure 3: Spatial distribution of maximum flow depth (a) and maximum momentum flux (b) in the Wellington CBD, modelled with the ESR approach.

We further compare the modelled maximum flow depth values between the ESR and ERB approach simulations to reveal the effects of explicitly buildings and to evaluate the performance of the ESR approach in built-up areas.

The grid-by-grid difference in the estimates of maximum flow depth has been calculated by subtracting the ESR maximum flow depth results from the ERB maximum flow depth results (Figure 4a). This difference has then been converted to percentage increase which reflects the proportional increase of the modelled results using the ERB approach compared with the ESR approach. Note that the comparisons are only made at the grids where both simulations have modelled results. This means that no comparisons are made within the footprints of the buildings if tsunami does not overtop them.

The results reveal that the ERB approach gives maximum flow depth estimates about 20-60% higher than the ESR approach in most places along the water front of the Wellington CBD (Figure 4b). In some areas further inland, roughly outlined by the black ovals in Figure 4b, the ERB approach gives maximum flow depth estimates up to 20% lower than the ESR approach due to the blocking/shielding effect of the buildings and structures near the water front.

It is obvious that the ESR approach modelling in the current practice may significantly underestimate tsunami flow depth near the water front of built-up areas, and overestimate the depth in some areas further inland, as we observe in the Wellington CBD. A similar level of inaccuracy may also be expected in the current practice of tsunami damage, loss and risk assessments, resulted from the ESR approach modelling.

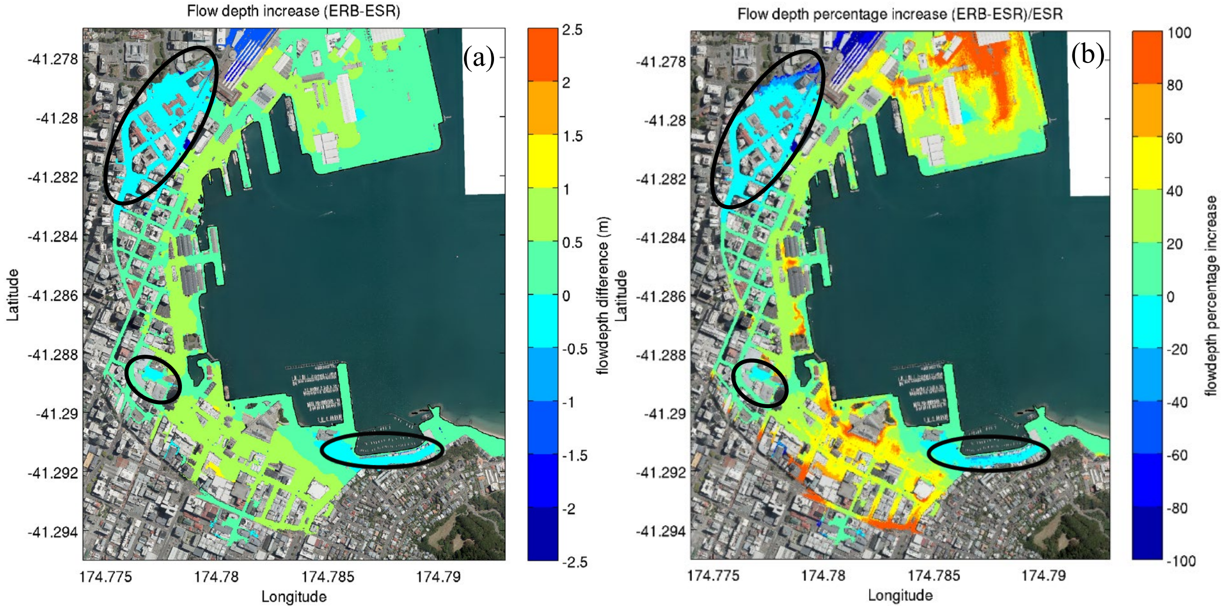

Figure 4: Comparisons of maximum flow depths between the ERB and ESR approaches at the Wellington CBD. (b) the colour scale shows flow depth value increase; (b) the colour scale shows flow depth percentage increase. Black oval areas indicates where the ERB approach gives smaller flow depth than the ESR approach.

In summary, we find that the ESR approach will significantly underestimate tsunami flow depth in built-up areas, especially close to water front. It may not be surprising to see an underestimate of up to 60% in flow depth, which may result in inaccuracies up to a similar level in tsunami damage, loss and risk assessments in these areas. Furthermore, maximum flow depth does not spatially correlate well with maximum momentum flux due to its large dependency on topographic variations. This adds uncertainties and inaccuracies in the current tsunami damage, loss and risk assessments, additional to the inaccuracy in flow depth estimate from the ESR modelling.

Therefore, tsunami flow depth is not the ideal option to be used as the sole hazard intensity measure in fragility functions, especially when flow depth values obtained from ESR modelling are used. Ideally, momentum flux (or other parameters combining effects of flow depth and flow velocity) is a better, theoretically consistent candidate. However, momentum flux is hardly measurable in post tsunami surveys and the use of momentum flux as the key hazard intensity parameter in fragility functions requires extensive tsunami inundation modelling work and the availability of high resolution data.

Tsunami flow depth is the easiest, often the only, hazard parameter that can be measured and thus used for the development of fragility functions. The current practice is still the most practical way for tsunami damage, loss and risk assessments.

Considering this, we further comment that fragility functions using flow depth from ESR modelling as the sole intensity parameter might be suitable for tsunami damage, loss and risk assessments over a large area so that (hopefully) discrepancies become not statistically important, as shown by the study of Song et al. (2018). However, such fragility functions may not be suitable to be used for small areas, especially for specific buildings near the foreshore, where site specific, detailed hydrodynamic modelling is highly recommended.

4 CONCLUSIONS

Flow depth is not an effective and suitable parameter to be used as the sole tsunami hazard intensity measure in fragility functions, especially when its values from ESR modelling are used. Current practice may lead to very large inaccuracies in tsunami damage, loss and risk assessments. Ideally, momentum flux (or other parameters combining effects of flow depth and flow velocity) is a better, theoretically consistent IM. However, momentum flux is hardly measurable in post tsunami surveys and its use as the key hazard intensity parameter in fragility functions requires extensive tsunami inundation modelling work and the availability of high-resolution data in order to establish its link to flow depth, the easiest and often the only hazard parameter that can be measured. Therefore, using flow depth as the key hazard IM in fragility functions still remains a practical way for tsunami damage, loss and risk assessments, with their potentially large inaccuracies in mind. However, such fragility functions may not be suitable for small areas, especially for specific buildings near the foreshore, where site specific, detailed hydrodynamic modelling is required.

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