Effect of explicitly representing buildings on tsunami inundation: a pilot study of Wellington CBD

X. Wang

Department of Tectonophysics, GNS Science, Lower Hutt, New Zealand

W.L. Power, B. Lukovic & C. Mueller

GNS Science, Lower Hutt, New Zealand

2017 NZSEE Conference

ABSTRACT: In tsunami losses and risk assessments maximum tsunami flow depth and flow speed have been widely used as key parameters for estimating building damage and fatalities in fragility functions. These parameters are commonly obtained through numerical simulations with the Equivalent Surface Roughness (ESR) approach in which ground-level buildings are deliberately removed and replaced with corresponding ESR values for tsunami inundation modelling. In this study, which uses an Mw 9 Hikurangi earthquake scenario, the effects of explicitly representing buildings (ERB) on estimates of tsunami flow depth and flow speed were investigated for Wellington CBD in New Zealand. With a meter-level grid spacing, individual buildings were well resolved and treated as solid-filled blocks that remain standing during tsunami impact, which is likely to happen in well-built urban areas like Wellington CBD. The modelling results reveal that in most CBD areas maximum flow depths with the ERB approach are about 0.5 to 1.0 meters (i.e. over 50 percent) higher than those predicted with the widely adopted ESR approach. The difference in maximum flow speeds is even bigger. In most waterfront areas, the ERB approach gives an estimate of maximum flow speeds typically 1.0-3.0 m/s (i.e. over 80 percent) higher than the ESR approach does. Our findings reveal potentially very large uncertainties in current tsunami loss and risk assessments that have been using maximum flow depth and flow speed commonly obtained with ESR approaches as key parameters in the evaluation of fragility functions, especially in urban areas of high social and economic importance.

1 INTRODUCTION

In tsunami loss and risk assessments, maximum tsunami flow depth and flow speed have been widely used as key parameters for estimating building damage and fatalities in fragility functions (Suppasri et al., 2012; Charvet et al., 2015). These parameters are commonly estimated through numerical simulations with the Equivalent Surface Roughness (ESR) approach. In this approach, existing ground surface appendages, such as buildings and vegetation, have usually been removed and replaced with equivalent surface roughness values, e.g., Manning’s n (Wang and Power, 2011). These roughness values were deliberately chosen in correlation to different types of land covers and building densities so that the retarding effect of these ground appendages on incoming tsunami flows, typically modelled as bottom frictions with given roughness values, can lead to an overall agreement with field observations and other studies in terms of inundation extents and overall attenuation rates of tsunami height as water travels further inland.

This ESR approach has been a reasonable option for numerical simulations in tsunami hazard analysis, as a result of technical compromises among the availability of high resolution Digital Elevation Model (DEM) data and land-cover information, the efficiency of computational hardware, and the capability of numerical simulation models. Because of these constraints, tsunami inundation modelling has been using a spatial resolution mostly ranging from around 10 to a few 10s meters which is too coarse to include buildings explicitly in the numerical modelling.

However, the ESR approach only provides a rough spatially averaged estimate on the effect of ground buildings on tsunami flows. The removal of ground surface buildings will inevitably change the flooding pattern of a tsunami and therefore result in different spatial and temporal distributions of flow depths and flow speeds from what they would be, especially in central urban areas where buildings are typically well constructed and unlikely to collapse during tsunami impact. Consequently, tsunami inundation modelling with this ESR approach may present large uncertainties in tsunami hazard analysis, especially in tsunami loss estimates in which damages and casualties are typically functions of modelled flow depth at given sites. Strictly speaking, the ESR approach is not physically appropriate to model the effect of buildings and vegetation on tsunami flow as the method was originated from bottom friction modelling for open channel flows where roughness features are all fully submerged while this is not the case for buildings and vegetation in tsunami flow.

In this study, with an improved modelling capability, the effects of explicit inclusion of individual buildings on tsunami inundation modelling have been investigated in a scenario event to reveal possible uncertainties in the estimates of maximum flow depth and flow speed that have been commonly obtained with the ESR approach.

2 STUDY SITE AND SOURCE SCENARIO

The Wellington region of New Zealand 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 in the southern North Island (Wallace et al., 2012), and it is also cut by a number of major local faults, such as the Wellington Fault, Wairarapa Fault and Wharekauhau Fault (Figure 1 left panel). Historically, the coastal suburbs of Wellington have been affected by tsunamis originating from both local sources and distant ones (Grapes and Downes, 1997). The Hikurangi subduction zone is a likely source of the largest magnitude earthquakes in the study area, and a likely source of major tsunami.

In this study, a Hikurangi Mw9 earthquake scenario by Cousins et al. (2007) was adopted as the source scenario for subsequent tsunami simulations in this study. 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. The rupture length is approximately 300 km of which only a small fraction, about 15%, is in the strait. Although the south-west termination of such a rupture is not well constrained by past GPS studies as no seabed stations have been deployed, such a scenario cannot be ruled out and would have to be seen as a worst case scenario for Wellington. As shown by the computed vertical displacement in Figure 1 (right panel), the Wellington region is mostly subsided, making it prone to severe flooding in Wellington CBD and therefore ideal to examine the effect of buildings on tsunami inundation.

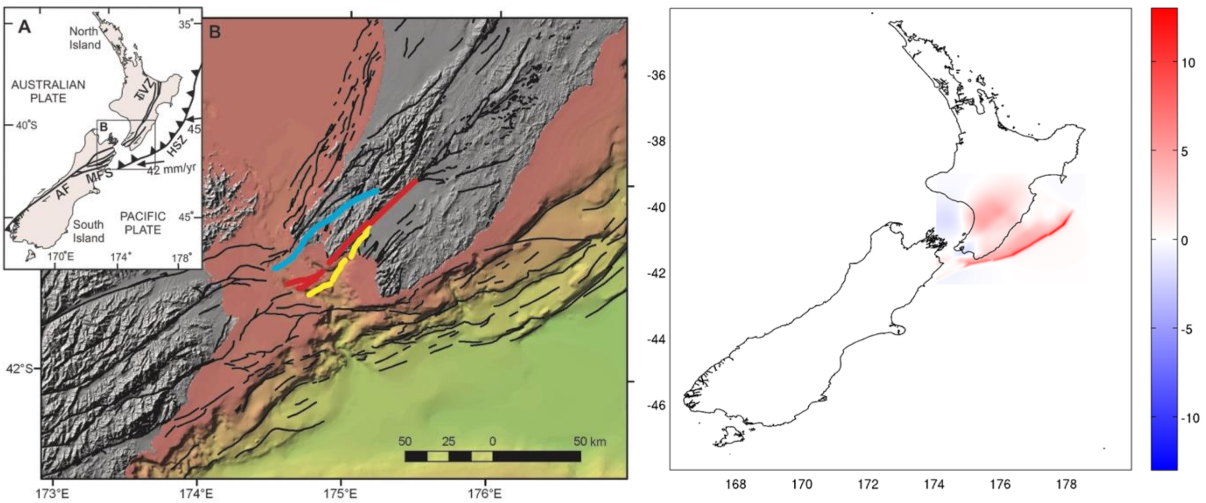

Figure 1. Left panel shows tectonic setting of the study site. Bold blue line = Wellington Fault, bold red line = Wairarapa Fault, and bold yellow line = Wharekauhau Fault, HSZ in inset = Hikurangi subduction zone (Robinson et al., 2011); right panel shows the vertical displacement of the Mw9 Hikurangi scenario in meters.

3 NUMERICAL MODELLING

Two sets of numerical simulations have been performed to investigate the effects of buildings on tsunami flow depths and flow speeds at Wellington CBD. In one simulation, the ERB approach has been used in order to explicitly evaluate the effects of individual buildings on the calculated maximum tsunami flow depth and flow speed. In the other simulation, maximum flow depth and flow speed have been computed with the traditional ESR approach that has been widely used in tsunami hazard assessments. For both simulations in this study, tsunami is assumed to arrive in coincidence with Mean High Water Spring (MHWS), i.e., Mean Sea Level (MSL)+0.69 m in the Wellington Harbour, which remains unchanged during the simulated duration of three hours after the earthquake.

3.1 Tsunami Model

For both simulations, a tsunami model - COMCOT (Cornell Multi-grid Coupled Tsunami) was used to simulate the tsunami generation, propagation and coastal inundation caused by the Hikurangi source scenario. COMCOT was originally developed by the wave research group at Cornell University, USA (Cho, 1995; Wang, 2008). It has subsequently been under continued development at GNS Science, New Zealand (Wang and Power, 2011). This numerical model is capable of simulating the entire life-span of a tsunami, including its generation by earthquakes and landslides, transoceanic propagation, coastal run-up and inundation. It uses explicit staggered leap-frog finite difference schemes to solve linear and nonlinear shallow water equations in either spherical or Cartesian coordinates to catch the dynamics of tsunami waves (Wang and Liu, 2007;2011). An ad-hoc parameterized wave breaking model (Kennedy et al., 2002; Lynett, 2002) together with the dissipation mechanism associated with the numerical schemes in COMCOT (Wang and Power, 2011) has been used to empirically estimate the effects of energy dissipation in association with wave breaking and tsunami bores during tsunami shoaling and inland flooding.

3.2 Modelling Grids

The tsunami simulation model COMCOT uses a series of nested 'grids' at cascading grid spacing, constructed from bathymetric and topographic data, to account for spatial resolution requirements by a tsunami travelling through different regions, e.g. deep ocean basins, continental shelves, nearshore regions and inlands. In this study, five levels of DEM grids were used to simulate the generation of tsunami from the source scenario, offshore propagation and potential coastal flooding in the coastal areas of Wellington, including its CBD, with increasing detail. For all these DEM grids, both water depth and land elevation are defined in terms of MSL.

The first level grids cover the whole Pacific at a spatial resolution of 2 arc-minutes (~3600 m at Equator), derived from the NGDC ETOPO topographic and bathymetric database and used to simulate tsunami generation and propagation from source regions. The second level grids were derived from LINZ Charts, the Seabed Mapping CMAP and GEBCO 08 datasets that covers the whole New Zealand and its offshore regions at 30 arc-seconds (~650-750 m in New Zealand). The third level grids, derived from the same sources as the second level, cover the southern part of North Island at a spatial resolution of 4.2 arc-seconds (~95 m in Wellington Region).

The fourth level grids, covers the Wellington Harbour and its surrounding suburbs at a spatial resolution of about 9 meter (left panel in Figure 2). This high resolution DEM data is necessary for detailed tsunami propagation and inundation simulation in the coastal areas of Wellington, and is derived from a combination of LiDAR (Light Detection and Ranging) topographical data provided by Wellington Regional Council and multi-beam bathymetric survey data from NIWA (Pallentin et al., 2009) in Wellington harbour. The fifth level grids have the highest spatial resolution at a grid spacing about 1.5m meters, covering the CBD area of Wellington as shown in the right panel of Figure 2. This resolution was determined by balancing the capability of resolving building footprints against computational time.

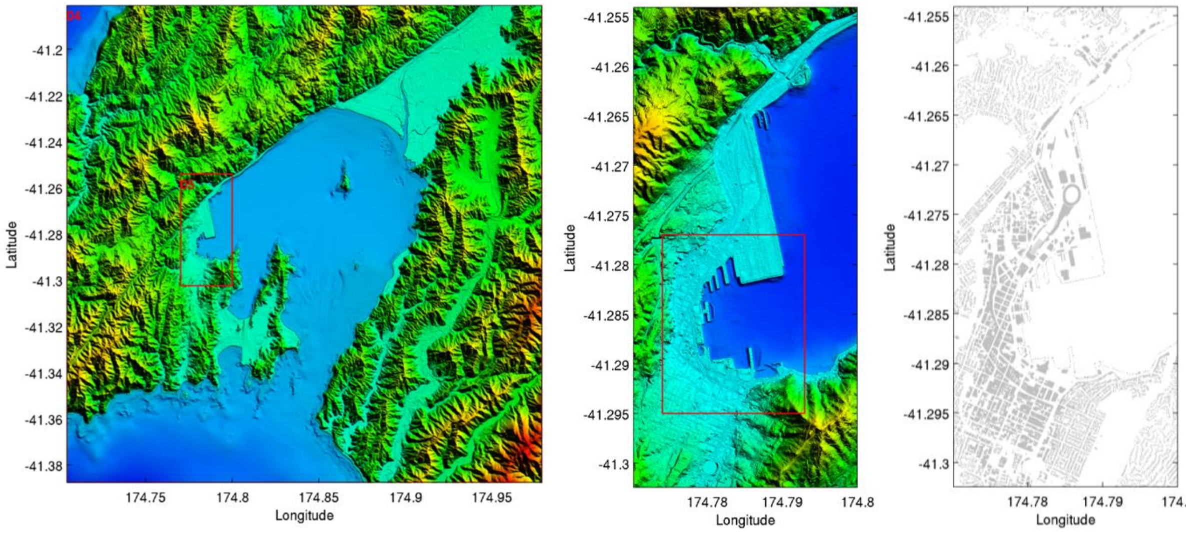

Figure 2. Left panel: the fourth level grids covering the entire Wellington Harbour region at 9 m grid spacing; middle panel: the fifth level grids covering the entire Wellington CBD at 1.5 m spacing (ground-level DEM with complete removal of all the buildings). Right panel shows the footprints of all the buildings as grey colour shaded polygons. The red box in the middle panel outlines the central Wellington CBD area where detailed analysis of the modelling results has been made.

3.3 Building Treatment and Roughness Values

In the simulation with the ERB approach, individual buildings were explicitly represented as impermeable solid-filled blocks, constructed from the footprints of the buildings with their correct heights. It was further assumed that these buildings would survive from the earthquake and also remain standing during the subsequent tsunami impact. Manning's n = 0.025 was used for the open spaces outside the buildings, e.g., parks, squares, parking spaces and streets (white areas between building footprints in the left panel of Figure 3).

In the ESR approach simulation, a ground surface roughness, n = 0.06, was adopted in Manning's friction model to approximate the retarding effect of ground surface features such as vegetation and buildings on tsunami inundation at the Wellington CBD. These values have been typically used for tsunami inundation studies at urban built-up areas and urban open areas, such as in Power et al. (2016).

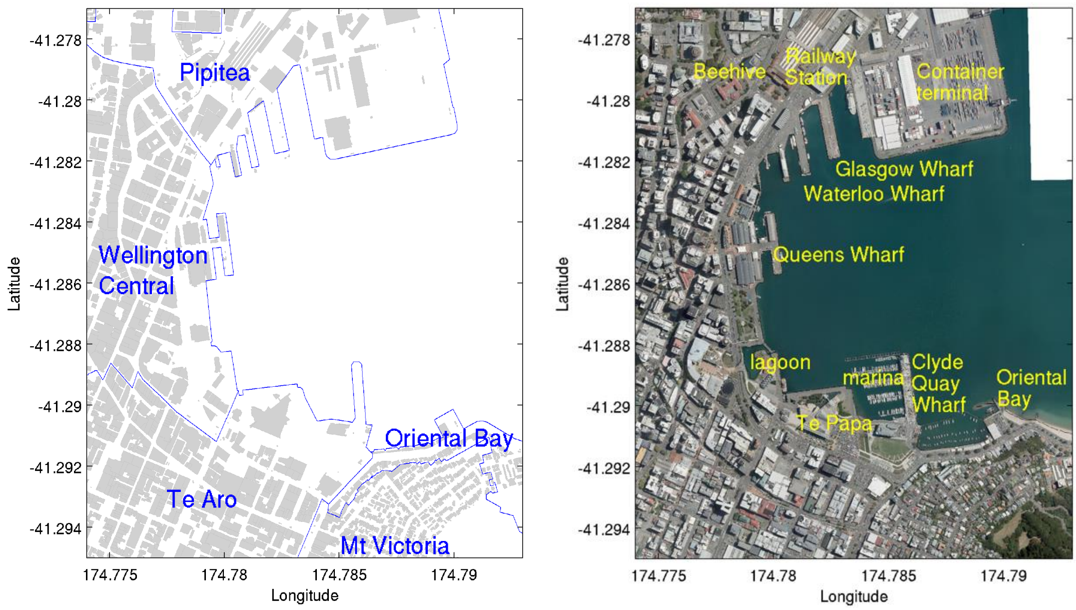

Figure 3. Left panel shows building footprints in central Wellington CBD as grey colour polygons. Right panel shows a corresponding satellite image with the same coverage and labels of some major landmarks

4 RESULTS AND DISCUSSIONS

Both the maximum flow depth and flow speed have been calculated through the numerical simulations with the ERB approach and the ESR approach, respectively. Figure 4 shows the spatial distributions of the computed inundation extents, maximum flow depths and flow speeds in the CBD area, modelled with the two approaches.

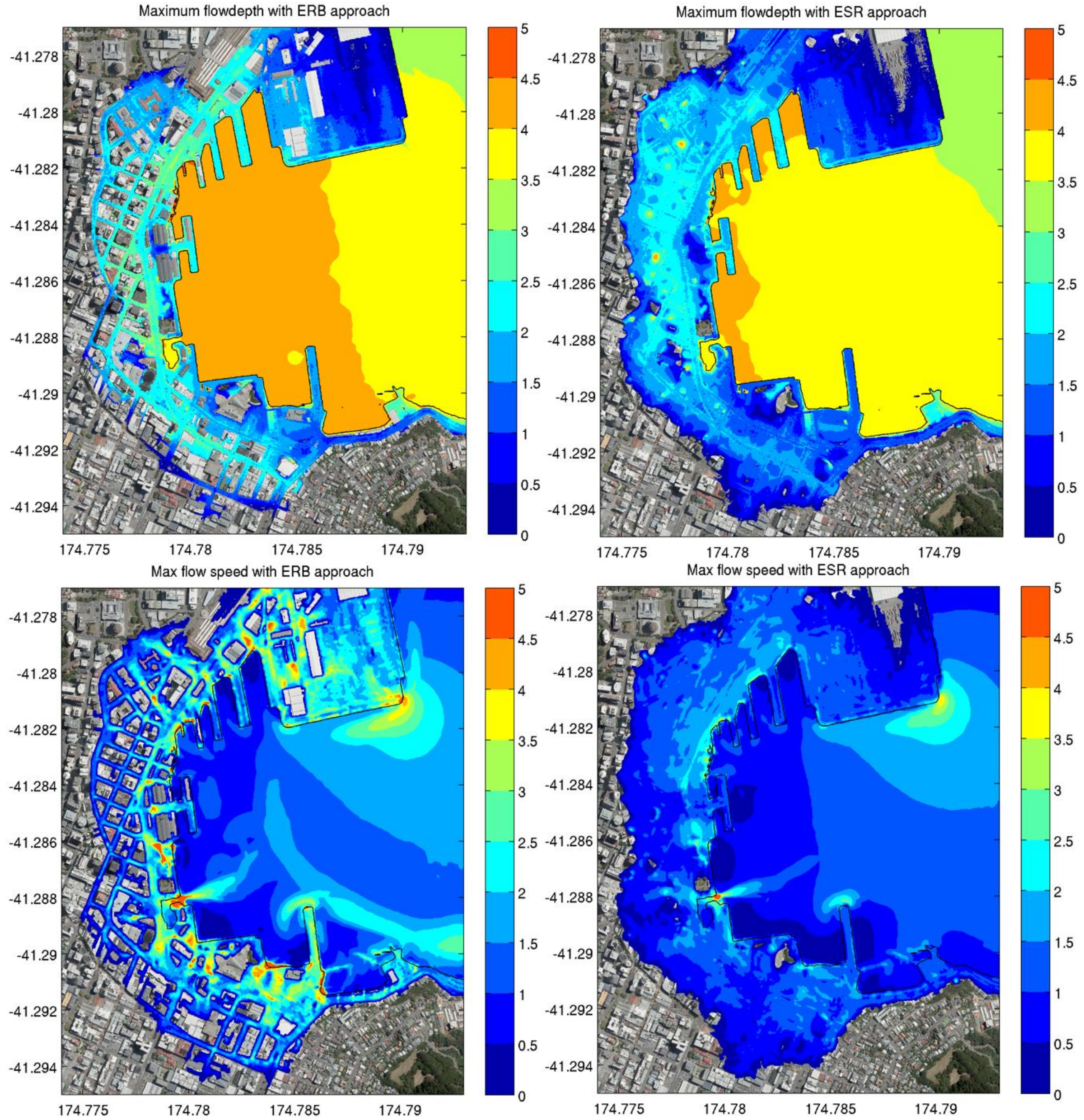

Figure 4. Upper left panel: computed maximum flow depth with the ERB approach; Upper right panel: computed maximum flow depth with the ESR approach. For both upper panels, colour scales indicate flow depth on land or tsunami elevation in water in meters. Lower left panel: computed maximum flow speed with the ERB approach; Lower right panel: computed maximum flow speed with the ESR approach. For both lower panels, colour scales indicate flow speed in m/s.

The upper two panels of Figure 4 illustrate that both approaches lead to a similar flooding extent, except for the inland areas behind the Railway Station (close to the top edge of the panel, also refer to Figure 3) where the impermeable solid block assumption on the covered platforms and parking buildings alongshore create artificial vertical walls, blocking tsunami from flowing further inland and stacking much larger flow depth in the water front side. However, the overall similarity of inundation extents for the two approaches may also be a result that tsunami inland flows reach step slopes at roughly 5 m above MSL.

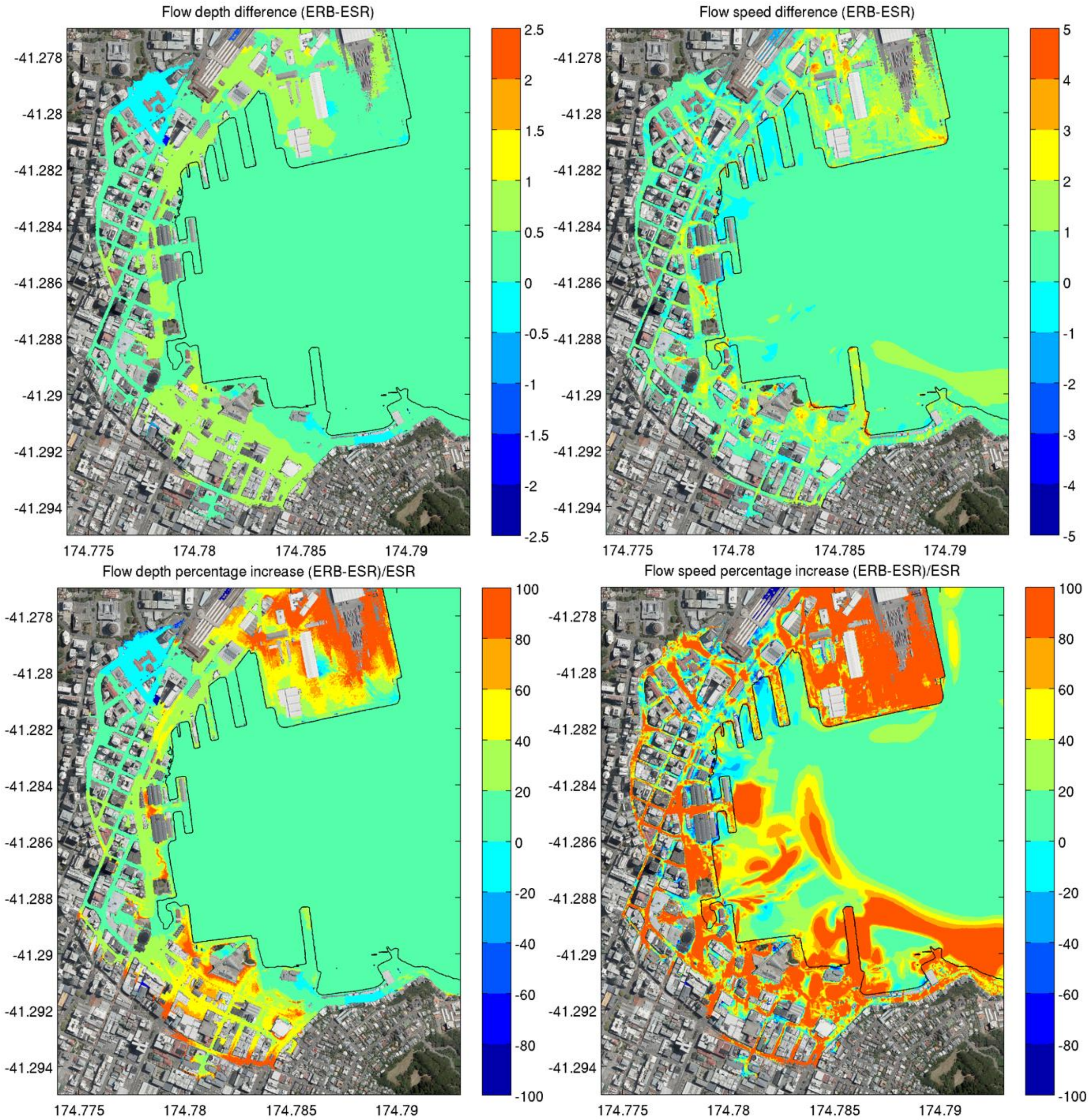

Figure 5. Comparisons of maximum flow depth and flow speeds between the ERB and ESR approaches. Upper left panel: the flow depth differences of the ERB results subtracting the ESR results in meters. Upper right panel: the flow speed differences of the ERB results subtracting the ESR results in meters per second (m/s). Lower left panel: the percentage increase in maximum flow depths of the ERB results to the ESR results. Lower right panel: the percentage increase in maximum flow speeds of the ERB results to the ESR results. For both lower panels the colour scales indicate the percentage values.

For the numerical simulation with the ERB approach, the modelled maximum flow depth (the upper left panel in Figure 4) ranges mostly from 2.0 to 3.5 meters in Wellington Central, and from 1.5 to 3.0 meters around Te Papa and further inland. The modelled maximum tsunami flow speeds (the lower left panel in Figure 4) are mostly within the range of 1.5 to 5.0 m/s at the waterfront from Clyde Quay Wharf to ferry terminals (refer to Figure 3 for the landmark locations). In contrast, for the numerical simulation with the ESR approach, the modelled maximum flow depth (the upper right panel in Figure 4) ranges mostly from 1.0 to 2.5 meters in Wellington Central, and from 0.5 to 2.0 meters around Te Papa and further inland. At a few spots, the modelled maximum flow depth reaches 3.5-4.0 meters, but they are likely the result of incorrect treatments of building removals in the DEM. The modelled maximum tsunami flow speeds (the lower right panel in Figure 4) mostly fall to the range of 0.5 to 3.0 m/s at the waterfront from Clyde Quay Wharf to Glasgow Wharf (refer to the right panel of Figure 3 for locations).

To further reveal the effects of buildings on the modelled tsunami flow depth, the difference between the modelling results of the two approaches has been calculated by subtracting the ESR results from the ERB results (upper panels in Figure 5). This difference has also been converted to percentage increase which reflects the increase of the modelling results in percentages when comparing the ERB approach results to the ESR approach results (lower panels in Figure 5). Note that the comparisons are made only at the locations where both simulations have flow depth and flow speed data available. This means no comparisons are made within the footprints of the CBD buildings.

The comparisons reveal that in most places of Wellington CBD the tsunami flow depths modelled with the ERB approach are up to 1.0 meter higher than those modelled with the ESR approach (upper left panel in Figure 5) which represent over 50% increase in the flow depth estimates (lower left panel in Figure 5). The difference in the estimates of the maximum flow speed is even bigger. The maximum flow speed modelled with the ERB approach is typically 1.0 to 3.0 m/s higher than that modelled with the ESR approach (upper right panel in Figure 5) which gives a percentage increase of over 80% in most of places (lower right panel in Figure 5). The explicit inclusion of all the buildings in the ERB approach also pushes the maximum water level inside the harbour about 0.5 meters higher than that modelled with the ESR approach, due to the blocking effect of coastal buildings on the incoming tsunami flow.

Though this scenario-based study, it is obvious that for urban areas like Wellington CBD the ERB approach will give significantly higher estimates on both tsunami flow depth and flow speed than the traditional ESR approach. The large differences in the estimates of maximum flow depth and flow speed between the two approaches may imply potentially a very large uncertainty in current tsunami loss and risk assessments. In these assessments the ESR approach has been widely used to obtain these two key parameters in the underpinning fragility functions. This large uncertainty may greatly affect the effectiveness of tsunami hazard assessments, land-use planning, and tsunami mitigation measures such as the determination of minimal safe heights for vertical evacuations, as outlined in FEMA (2012) and the 2016 Edition of ASCE 7 *Minimum Design Loads For Buildings and Other Structures*.

Note that the uncertainty caused by the different treatment of buildings is among many other uncertainties such as those in source parameter estimates, numerical models and the quality of DEM data. Further research is required to quantity these uncertainties and codify their effects in probabilistic tsunami hazard assessments.

5 CONCLUSION

A numerical investigation has been made to study the effect of explicit buildings on the estimate of maximum tsunami flow depth and flow speed at Wellington CBD in New Zealand, using an Mw9 Hikurangi earthquake scenario. In this study, with a 1.5m spacing grids individual buildings were treated as solid-filled blocks and assumed to remain standing during tsunami impact which is likely to happen in well-built urban areas like Wellington CBD.

The modelling results indicate that in most areas of Wellington CBD the ERB approach, more suitable for solid built urban areas, predicts the maximum tsunami flow depth about 0.5 to 1.0 meters, i.e. over 50 percent, higher than the widely adopted ESR approach in which ground buildings have been deliberately removed and replaced with equivalent surface roughness values for inundation modelling. The difference in the estimates of maximum flow speeds is even bigger. In most waterfront areas and in the water, the ERB approach gives an estimate of maximum flow speeds typically 1.0-3.0 m/s, i.e. over 80 percent, higher than the ESR approach does.

These findings reveal potentially very large uncertainties in current tsunami loss and risk assessments that have been using maximum flow depth and flow speed, commonly obtained with ESR approaches, as underlying key parameters in the evaluation of fragility functions. This is alarming as such uncertainties may greatly affect the effectiveness of tsunami hazard assessments, land-use planning, and tsunami mitigation measures such as the determination of safe heights for vertical evacuations, especially in urban areas of significant social and economic importance where buildings are usually dense and well built.

6 ACKNOWLEDGEMENTS

This study was funded by It's Our Fault project, GNS Science Capability Funds and National Natural Science Foundation of China (NSFC award number 41528203). Their supports are gratefully appreciated. The authors also gratefully acknowledge NIWA, GWRC and the Department of Conservation (DoC) for giving permission to use their multi-beam bathymetry dataset of Wellington Harbour for this study (Wellington Harbour Bathymetry, 1m digital grid, Pallentin et al., 2009).

7 REFERENCES

Charvet, I., Suppasri, A., Kimura, H., Sugawara, D. & Imamura, F. (2015). A multivariate generalized linear tsunami fragility model for Kesennuma City based on maximum flow depths, velocities and debris impact, with evaluation of predictive accuracy. *Nat. Hazards*, 79, 2073–2099.

Cho, Y.-S. (1995). *Numerical simulation of tsunami and runup*. PhD thesis, Ithaca, New York, Cornell University.

Cousins, W. J., Power, W. L., Destegul, U. Z. & King, A. B. (2007). *Combined earthquake and tsunami losses for major earthquake affecting the Wellington Region*. GNS Science Consultancy Report 2007/280. Lower Hutt. GNS Science.

FEMA. (2012). Guidelines for design of structures for vertical evacuation from tsunamis. FEMA Report P-646, 2nd edition. Applied Technology Council. Redwood City, California. pp174.

Grapes, R. & Downes, G. (1997). The 1855 Wairarapa, New Zealand, earthquake – Analysis of historical data. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 30(4), 271–368.

Kennedy, A.B., Chen, Q., Kirby, J.T. & Dalrymple, R.A. (2000). Boussinesq modeling of wave transformation, breaking, and runup. part i: 1d. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 126(1):39–47.

Lynett, P. (2002). *A Multi-layer approach to modelling generation, propagation, and interaction of water waves*. PhD thesis, Ithaca, New York. Cornell University.

Okada, M. (1985). Surface deformation due to shear and tensile faults in a half space. *Bulletin of the Seismological Society of America*, 75(4), 1135–1154.

Pallentin, A., Verdier, A.L. & Michell, J.S. (2009). *Beneath the waves: Wellington Harbour NIWA Chart*, Miscellaneous Series, No. 87.

Pondard, N. & Barnes, P.M. (2010). Structure and paleoearthquake records of active submarine faults, Cook Strait, New Zealand: Implications for fault interactions, stress loading, and seismic hazard. *Journal of Geophysical Research* 115, B12320. doi:10.1029/2010JB007781.

Power, W. (ed.). (2013). *Review of tsunami hazard in New Zealand (2013 update)*. GNS Science Consultancy Report 2013/131. Lower Hutt. GNS Science.

Power, W.L., Horspool, N.A., Wang, X. & Mueller, C. (2016). *Probabilistic mapping of tsunami hazard and risk for Gisborne City and Wainui Beach*. GNS Science consultancy report 2015/219. 79 p. Lower Hutt. GNS Science.

Robinson, R., Van Dissen, R. & Litchfield, N. (2011). Using synthetic seismicity to evaluate seismic hazard in the Wellington region, New Zealand. *Geophysical Journal International* 187 (1): 510-528.

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K. & Imamura, F. (2012). Developing tsunami fragility curves from the surveyed data of the 2011 Great East Japan tsunami in Sendai and Ishinomaki plains. *Coast. Eng. J.*, 54, 1250008.

Wang, X. (2008). *Numerical Modelling of surface and internal waves over shallow and intermediate water*. PhD thesis, Ithaca, New York. Cornell University.

Wang, X. & Liu, P. L. F. (2007). Numerical simulation of the 2004 Indian Ocean tsunami – Coastal Effects. *Journal of Earthquake and Tsunami*, 1(3), 273–297.

Wang, X. & Liu, P. L. F. (2011). An explicit finite difference model for simulating weakly nonlinear and weakly dispersive waves over slowly varying water depth. *Coastal engineering*, 58(2): 173-183.

Wang, X. & Power, W. L. (2011). *COMCOT: A Tsunami Generation Propagation and Run-up Model*. GNS Science Report 2011/43. Lower Hutt. GNS Science.