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# Comparison of building damage loss estimates from two alternative tsunami models

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## ABSTRACT

New Zealand's entire coastline is at risk of tsunami. The potential for significant losses from tsunami impact has been demonstrated by events such as the 2011 Tohoku earthquake in Japan, which shares a similar tectonic setting with New Zealand. While we cannot prevent such a tsunami event from happening, actions (e.g., devising adequate risk mitigation strategies) can be taken to increase our communities' resilience and reduce potential impacts.

Decision-making on appropriate actions commonly requires quantitative information on possible consequences, e.g., building damage losses and casualties estimates. These can be produced by undertaking risk assessments. For the risk estimates to be reliable, it is necessary that all the complex phenomena taking place during a real event must be simulated as accurately as possible. However, approximations/simplifications and assumptions are typically needed in such assessments as effective modelling of all steps involved can be time-consuming. Also, detailed data and funds may not be readily available to carry out a comprehensive study. This paper presents potential implications on direct loss estimates (for a building portfolio) resulting from the application of two approximations of representing buildings in tsunami inundation modelling. In one approximation, buildings are explicitly represented as solid blocks (ERB); in the other, buildings are removed, and their effects are simply modelled using equivalent surface roughness (ESR). Comparative analysis of ultra-high resolution inundation simulations in built-up areas shows that for scenarios causing limited in-land flooding of the built-up area, the loss estimates from the ESR approximation can be appreciably underestimated. However, in the case of scenarios causing intense inundation of larger built-up areas, the loss estimates derived from the two approximations are closer. The use of the alternative fragility models for the modelled portfolio had a limited effect on the portfolio loss ratio between the two approximations.

Keywords: Tsunami inundation, tsunami fragility model, risk, building damage, direct loss, Hikurangi Subduction Zone.

## INTRODUCTION

New Zealand is exposed to a very high tsunami hazard [1]. The potential for significant human and economic losses from tsunami impact has been demonstrated by events such as the 2011 Tohoku-Oki earthquake and tsunami in Japan, which shares a similar tectonic setting with New Zealand. A similar event can be expected to strike New Zealand's coastal communities in the future [1]. While we cannot avoid such a disastrous event from happening, continued actions (e.g. devising adequate risk mitigation strategies) can be taken before the disaster, thus helping save money, lives and reducing community disruption [2].

To guide actions to minimize risk, quantitative information on possible consequences (e.g., estimates of building damage losses and casualties) are usually sought. Such risk estimates are typically produced by undertaking risk studies (e.g., [3] [4][5]); they generally involve convolving three key components:

- Asset model – database of the exposure portfolio of interest for which the risk estimates are to be derived. *This paper considers only direct loss estimates for a building portfolio*.
- Tsunami hazard model – output from this is an estimate of one or more tsunami intensity measures (IMs), such as maximum flow depth ($h_{max,}$ *chosen in this study*), at each building in the asset model exposed to a tsunami.

- Loss model – to calculate direct loss using a fragility model (links the tsunami IM and potential physical damage to the building) and a cost model (to translate physical damage estimate to monetary loss).

Each model above is characterized by many complexities and uncertainties. The output (i.e., loss estimate) can therefore carry a high degree of variability, as different simplifications and assumptions made to balance the available information, time and budget for the assessment can lead to different results. Reducing the uncertainties will improve the reliability of the output produced and consequently result in more effective actions. In this paper, we will present the potential implications on building loss estimates due to the application of two alternative approaches taken to represent the role played by buildings in tsunami inundation modelling. The effect of using alternative fragility models on loss comparisons from the two model setups will also be illustrated for a building portfolio.

This paper expands on a recent study by [6]; the same building exposure model created and tsunami scenarios modelled in [6] are also used here.

## ASSET MODEL

The study area is Napier, a city on the east coast of the North Island of New Zealand (Figure 1). It is a city that is highly exposed to tsunami hazard [7], and also has a vulnerable building stock - timber buildings represent over 95% of all buildings in the portfolio (~30,350 nos.). About 94% of the buildings in the portfolio are of one-storey height (see Table 1).

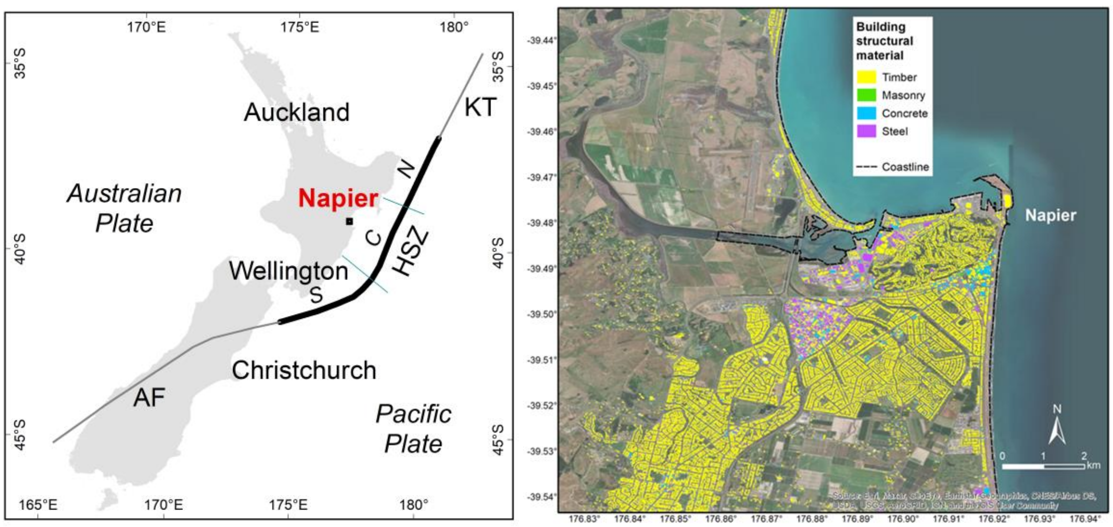



*Figure 1. Maps showing the location of Napier and the location of segments of the Hikurangi Subduction Zone (HSZ), a source of large earthquakes and tsunami (left) and buildings model (right). KT – Kermadec Trench, AF – Alpine Fault.*

*Table 1. Distribution of the total number of buildings and value of the modelled building portfolio.*

| No. of storeys | % no. of bldgs. | % bldg. portfolio value |
|---|---|---|
| 1 | 93.7 | 79.8 |
| 2-3 | 6.2 | 18.9 |
| >3 | 0.1 | 1.2 |
| Total (%) | 100 | 100 |

## TSUNAMI SOURCE SCENARIOS

Napier can expect a tsunami from local, regional, and distant sources. The potential to receive a tsunami from the Hikurangi Subduction Zone (HSZ) is high and has drawn attention in many studies (e.g., [7], [8]). It was also the chosen tsunami source region in [6]. Although it is desirable to consider a large number of scenarios, the computational cost of city-wide ultra-high-resolution modelling involved in this work restricts simulating only a few (of many plausible) scenarios from this source:

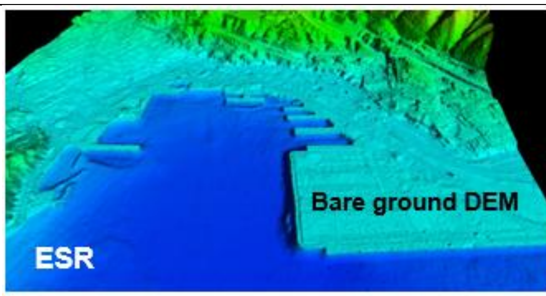
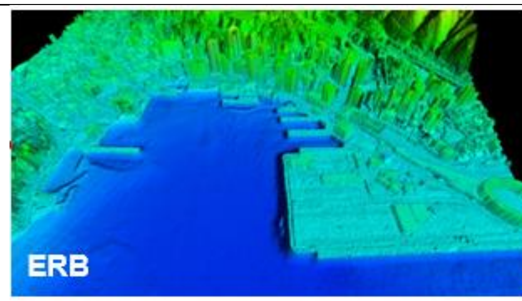
- $M_w$8.4 Hikurangi Earthquake - this scenario ruptures HSZ's central (C) segment offshore Hawke's Bay

- $M_w$8.8 Hikurangi Earthquake - this scenario represents a combined rupture of the southern (S) and central (C) Hikurangi segments
- $M_w$8.9 Hikurangi Earthquake - this scenario represents a combined rupture of the southern (S), central (C) and part of northern (N) Hikurangi segments
- $M_w$9.0 Hikurangi Earthquake - this scenario ruptures the whole Hikurangi subduction interface (all three segments).

## TSUNAMI INUNDATION MODELLING

Numerical modelling of tsunami involves several steps, including simulating water flow beyond the coastline to model in-land flooding. Many factors influence the different complex processes that take place during a real tsunami inundation. One of the key aspects requiring attention is how to model the retarding and flow redistribution effect by ground surface appendages (e.g., buildings) when they interact with the tsunami waves. To represent this in simulations, a roughness approach (ESR in Table 2) is typically adopted. In this case, buildings and other land features are removed (thus assuming open space on bare ground) and replaced with surface roughness values equivalent to various land covers, and inundation modelling is carried out. Due to this simple model setup, the computational efficiency is good; however, the tsunami flow patterns are not that well modelled, so the resulting IM estimates can carry significant inaccuracies ([9][10]). This limitation of the ESR approach is more pronounced in populated urban areas where large building densities render the open space assumption invalid. In such areas, a better approach to explicitly capture the role played by buildings is to represent them in inundation modelling. A simplified version of this approach is considered here (called ERB in Table 2, also see [6] for more details). Better reliable IM estimates can be obtained using the ERB approach; however, the downside is that the simulation time can be significantly higher than that of the ESR approach. This limitation makes the ERB approach less favourable for most practical applications[10].

*Table 2. Key features of the two alternative approaches taken to represent buildings in tsunami simulations[10].*

| **Equivalent Surface Roughness (ESR)** | **Explicitly Represented Buildings (ERB)** |
|---|---|
|  |  |
| • All the buildings (& other land-cover/ground features) are removed and replaced with spatially averaged, equivalent surface roughness value (e.g., Manning's roughness n = 0.06 for the entire built-up area) in the friction model to approximate their effects on tsunami flow[10].<br>• Simplified model setup and high computational efficiency. Spatial resolutions are typically 10 to a few 10s of metres. | • All the buildings explicitly represented as solid blocks on top of bare-ground DEM. Roughness values applied for all other features (as in ESR).<br>• Requires much higher spatial resolution - often at meter-level grid spacing, in order to sufficiently capture building footprints.<br>• Should incoming tsunami waves be taller than the building, overtopping of buildings is allowed and simulated in the modelling.<br>• Longer computational times, typically hundreds of times longer than the ESR approach, and no removal of destroyed buildings. |

*Note: the figures in this table are for illustration purposes only and do not show the study area coverage*

Aside from the different building treatments (i.e., ESR or ERB), all model settings for the comparative simulations were kept identical. The grid-by-grid difference (ERB vs. ESR), calculated as the percentage increase in the estimates of maximum flow depth of ERB over ESR for the four scenarios, is shown in Figure 2. Note that the comparisons are only made at the grids where both simulations have modelled results.

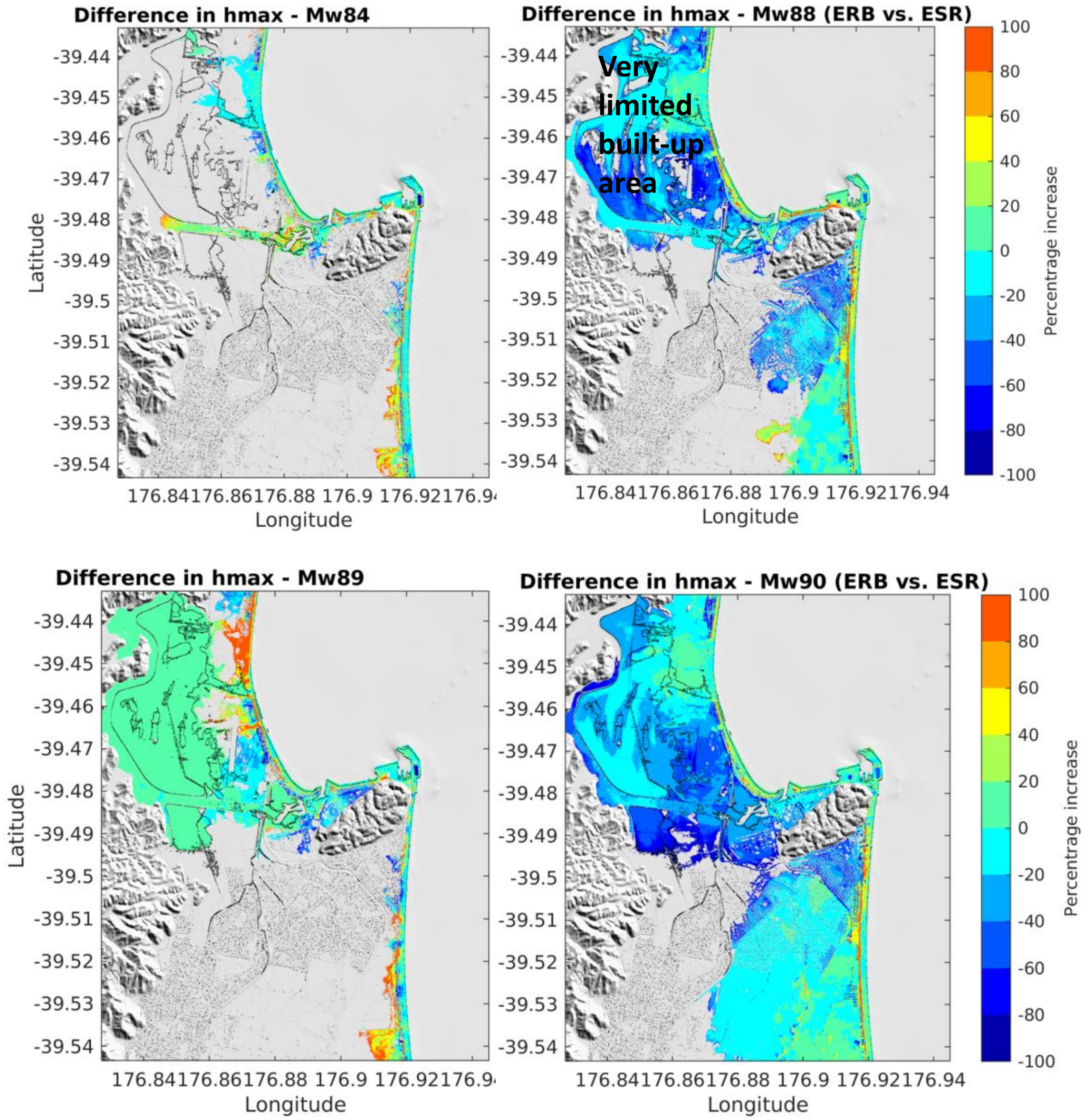



*Figure 2. Comparisons of estimated maximum flow depth ($h_{max}$) between the ERB and ESR approaches. Color-coded maps represent a percentage increase in maximum flow depth estimates of ERB over ESR.*

All scenarios inundate at least some parts of the study area; sections closer to the waterfront generally receive higher levels of flooding than those further inland. The estimated maximum flow depth from all inundated buildings ($Max\_h_{max}$) in each scenario is tabulated in Table 3; the maximum value considering all scenarios and both modelling approaches is approximately 10.5m (in ERB model exposed to $M_w$9.0 scenario).

$M_w$8.4 and $M_w$8.9 scenarios resulted in a limited extent of inundation of the built-up area. A similar number of buildings are flooded (see $T_{Bldgs\_inun}$ in Table 3) with both model setups, and there is a significant number of buildings having greater $h_{max}$ in ERB than in the ESR models.

Under the $M_w$8.8 and $M_w$9.0 scenarios, there is increased severity and spatial extent of flooding in the study area. Without the explicit presence of 'solid barriers' in ESR models, tsunami waves modelled tend to flow more freely and widely, thus inundating more buildings than ERB models (see Table 3).

*Table 3. Comparison of tsunami hazard modelling results for the building portfolio*

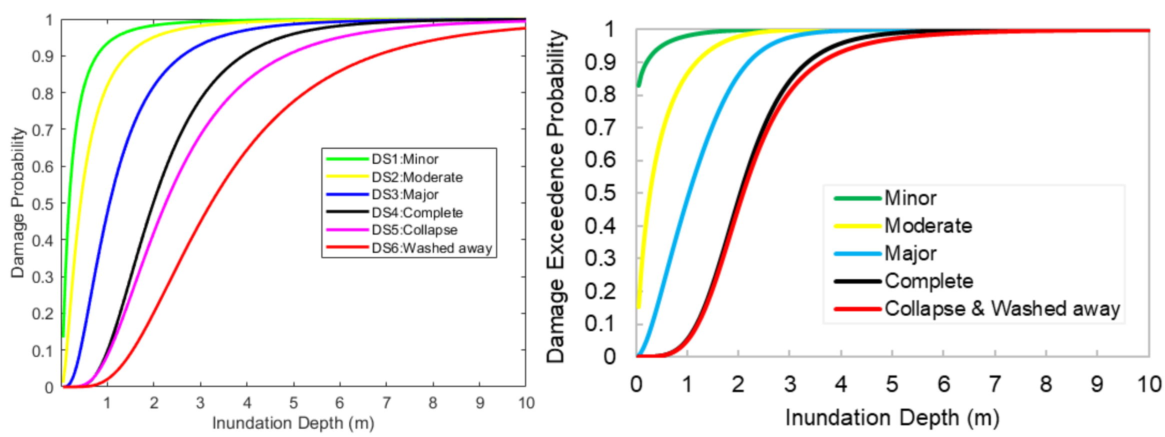
| Scenario | ESR Approach | | | | | ERB Approach | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Max_$h_{max}$ (m) | $T_{Bldgs\_inun}$ (#) | $h_{max}$ | | Bldgs. (#) | Max_$h_{max}$ (m) | $T_{Bldgs\_inun}$ (#) | $h_{max}$ | | Bldgs. (#) |
| | | | (%$^{ile}$) | (m) | | | | (%$^{ile}$) | (m) | |
| $M_W$8.4 | 4.2 | 2,688 (2,354)* | 90 | 0.86 | 2,419 | 6.7 | 2,732 (2,354)* | 90 | 2.03 | 2,459 |
| $M_W$8.8 | 8.2 | 12,831 (10,324)* | 90 | 2.86 | 11,548 | 10.4 | 10,625 (10,324)* | 90 | 4.41 | 9,563 |
| $M_W$8.9 | 4.8 | 3,146 (2,674)* | 90 | 1.43 | 2,831 | 6.1 | 3,115 (2,674)* | 90 | 2.71 | 2,804 |
| $M_W$9.0 | 8.4 | 16,586 (14,492)* | 90 | 3.39 | 14,927 | 10.6 | 14,596 (14,492)* | 90 | 4.43 | 13,136 |

* represents the number of buildings affected in both the ESR and ERB models (i.e., commonly inundated buildings)

## DAMAGE MODELLING

Fragility models are used to estimate potential physical damage to buildings from tsunami. Without such models specifically available for New Zealand buildings, models from overseas that could be mapped as closely as possible to the conditions here were needed for this study.

From the limited availability of tsunami fragility models in the literature, alternative models from two studies were found to be appropriate and readily available for use: (a) Suppasri [11]; (b) De Risi [12]. The models from these two works are empirical, i.e., based on extensive data (damage inspections conducted on over 200,000 buildings) that was compiled by the Ministry of Land, Infrastructure and Transportation of Japan (MLIT) following the 2011 Tohoku-Oki earthquake and tsunami. Linear regression analysis was performed in [11] to develop their proposed fragility models, whereas multinomial logistic regression was adopted in [12] to develop their models. The models consider 5-6 damage states (DS) for tsunami (see Figure 3 for example). Details on other commonalities and differences between the models (and the limitations of each) can be found in the respective studies or other works (e.g., [13][14]).




(a) (b)

*Figure 3. Fragility model for: (a) one-storey timber building [11]; (b) any timber building [12].*

The following three cases were considered to evaluate the effect of using these alternative fragility models on loss comparisons from the two model setups (i.e., ERB vs. ESR). For both the model setups, the cost model (from [6]) was kept the same in all three cases.

- Case 1 – Fragility models from Suppasri [11] assigned to all buildings in the modelled portfolio
- Case 2 – Fragility models from De Risi [12] assigned to all buildings in the portfolio
- Case 3 – Each building in the portfolio was assigned a model randomly (Figure 4)

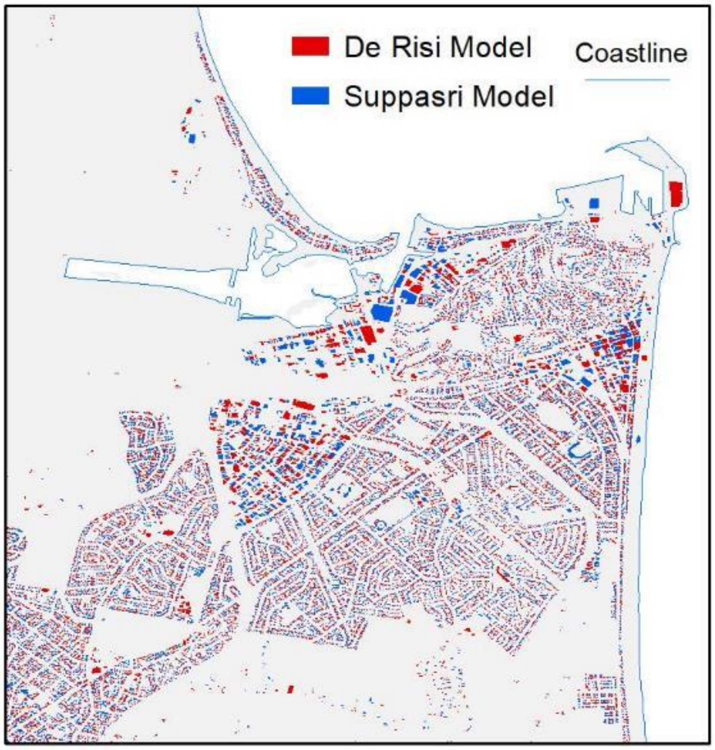


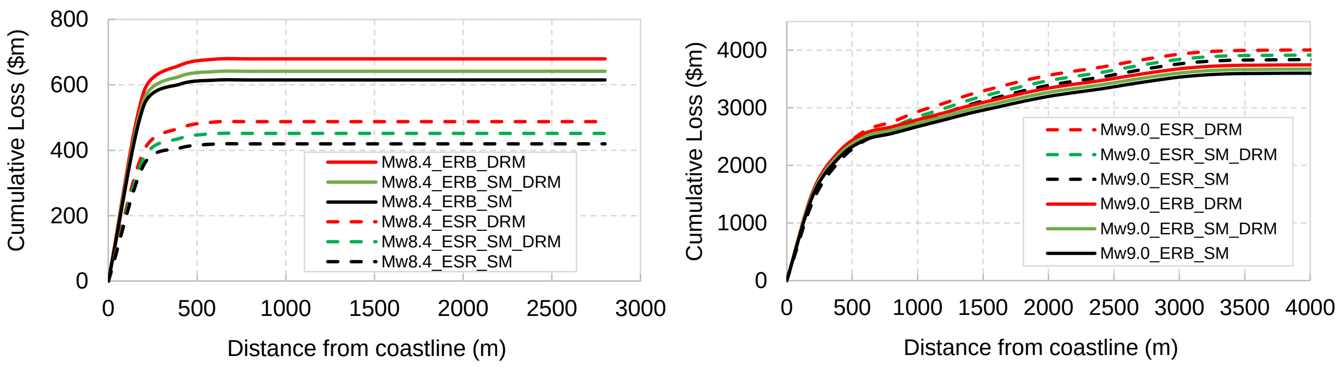

*Figure 4. Case 3 - Buildings with randomly assigned fragility model: Suppasri et al. [11] or De Risi et al. [12].*

**LOSS COMPARISONS**

Direct loss to each inundated building was estimated by multiplying the replacement value of the building with the damage ratio corresponding to the modelled maximum inundation (flow) depth at its location and the assigned building class. The loss to the building portfolio from each scenario was then calculated by summing up the losses from all the inundated buildings.

The following observations are made from the loss comparisons:

- The scenarios that resulted in limited inundation of the built-up area (i.e., $M_w$8.4 and $M_w$8.9) led to lesser portfolio losses when compared to losses from the scenarios that flooded a more significant number of buildings (i.e., $M_w$8.8 and $M_w$9.0, see Table 3). Among the four scenarios modelled, $M_w$8.4 and $M_w$9.0 were respectively the least and most damaging events for the modelled portfolio in all cases.
- A direct comparison of losses from the two model setups (i.e., ERB vs. ESR) can be made as shown in Figure 5 for buildings that were affected in both setups (i.e. commonly inundated buildings, see Table 3). Under the $M_w$8.4 scenario, the cumulative loss is higher with ERB. It is the opposite when exposed to the $M_w$9.0 scenario (i.e., ERB loss < ESR loss) due to no solid barriers in the ESR model and increased severity of flooding of the buildings.
- The use of De Risi fragility models (DRM) for all buildings (i.e., Case 2) resulted in higher losses when compared to the losses using Suppasri models (SM) for all the buildings (i.e., Case 1). The losses in Case 3 (i.e., fragility models randomly assigned: SM_DRM) lie in between these two cases. The above order of losses was observed for all the scenarios and with both the model setups; this can also be seen from the loss curves shown in Figure 5. However, as shown in Table 4, the adoption of the alternative fragility models in this study has limited effect on the portfolio loss ratio of ERB approach to ESR approach.




(a) (b)

*Figure 5. Cumulative loss curves for commonly inundated buildings due to: (a) $M_w$8.4 scenario; (b) $M_w$9.0 scenario.*

*Table 4. Comparison of Portfolio Loss Ratio (=ERB Loss/ESR Loss) calculated from cumulative loss from all inundated buildings in the modelled portfolio.*

| **Scenario** | **Portfolio Loss Ratio** | | |
|---|---|---|---|
| | **Case 1** | **Case 2** | **Case 3** |
| $M_w$8.4 | 1.51 | 1.43 | 1.46 |
| $M_w$8.8 | 0.95 | 0.94 | 0.94 |
| $M_w$8.9 | 1.28 | 1.28 | 1.28 |
| $M_w$9.0 | 0.88 | 0.88 | 0.88 |

## CONCLUSIONS

This study showed that the use of the typically adopted approach, i.e., equivalent surface roughness (ESR) approach, to represent buildings in tsunami inundation modelling in urban areas can lead to underestimation of direct losses, especially when a building portfolio such as the one modelled in this study is exposed to tsunami scenarios that can cause limited in-land flooding of the built-up area. The use of the better approximation approach, such as the explicitly representing buildings (ERB) approach, is favourable in scenarios with limited inundation in lands. On the other hand, the loss estimates derived from the two model setups get closer (i.e., lesser differences) when they are exposed to scenarios that cause widespread, intense inundation of the built-up area. The use of alternative fragility models for the building portfolio in this study resulted in limited variability in the portfolio loss ratio of ERB approach to ESR approach for the least damaging scenario of all the modelled scenarios. The portfolio loss ratios for the other scenarios were not sensitive to the choice of the alternative fragility models used in this study.

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