COMBINED TSUNAMI AND EARTHQUAKE LOSS FOR WELLINGTON, NEW ZEALAND

A.B King[1], W.J Cousins[1], W.L. Power[1], R. Blong[2], U.Z. Destegul[1], B. Weir[2], W.D. Smith[1]

[1] *Scientist, Hazards Group , GNS Science, Avalon, New Zealand*
[2] *Loss Modeller, Benfield, Sydney,Australia*
Email: a.kingt@gns.cri.nz

ABSTRACT :

Shaking damage arising from rupture of the Wellington Fault has long been regarded as being the Probable Maximum Earthquake Loss for New Zealand. Recently, however, this has been questioned following a probabilistic study of potential tsunami losses, which suggested that tsunami losses could greatly exceed earthquake losses for all levels of probability. With this in mind, we are aiming to estimate the combined earthquake plus tsunami PML for New Zealand.
Whereas the tsunami risk is relatively evenly spread over the length of New Zealand, the Wellington region by far dominates the earthquake risk, hence is likely to be the location of the greatest combined earthquake/tsunami risk. Modelling has therefore concentrated on potential tsunami-genic earthquakes in the Wellington Region. Five preferred sources have been modelled, including
• Wellington Fault (magnitude 7.5, highest earthquake loss of $12± 5 billion for an exposure of $77 billion),
• Wairarapa Fault 1 (magnitude 8.2, high earthquake loss, last ruptured in 1855 causing a tsunami, with this study calibrating well with the historical wave-height data observed).
• Subduction Zone (a likely major tsunami source, various models possible, but Wellington somewhat shielded from the tsunami by topography).
The overall results of the study have been confirmation that the maximum credible loss of Wellington remains dominated by earthquake shaking damage from the Wellington fault earthquake, with additional losses from tsunami from that event being negligible. Tsunami damage from other near field events could be appreciable but still much less than the Wellington earthquake shaking damage.

KEYWORDS: Loss estimation, tsunami, earthquake, combined losses,

1. INTRODUCTION

This paper outlines the methodology used and findings from a study into the combined earthquake shaking and tsunami induced losses for a near-field Wellington regional earthquake. In order to estimate the worst case scenario for loss, this project models the combined effect of earthquake induced ground shaking damage and of inundation from tsunami caused by such an event. The essential input features were major local source earthquakes, an assessment of their tsunamigenic potential and the resulting inundation/velocity characteristics that resulted therefrom. The damage state resulting from the earthquake shaking is assessed using earthquake shaking fragility parameters, and the subsequent tsunami inundation damage from tsunami inundation fragility functions that made allowance for each building class at its particular earthquake damage state. The project specifically focuses on the losses that result from earthquake induced shaking and subsequent tsunami inundation on buildings in the Wellington Region, New Zealand.

2 SEISMICITY

Seismicity in New Zealand varies regionally from moderate to very high on a world scale. New Zealand straddles the boundary of the Australian and Pacific plates where relative plate motion is obliquely convergent across the plate boundary. The relative plate motion is expressed in New Zealand by the presence of many active faults, a high rate of “small-to-moderate” earthquakes (M<7), the occurrence of many “large” earthquakes (M7-7.9) and one “great” earthquake (M>8) since 1840 when recording commenced (Figure 1). Wellington Region is located in the boundary zone between the Pacific and Australian plates. It lies above the Hikurangi subduction zone where the Pacific plate is sinking beneath the Australian plate, 25 km or so beneath Wellington City. Crustal strain caused by the inter-plate motions is accommodated by several active faults in the Region. One of the most active is the Wellington Fault which runs through the centre of the urban area, ruptures on average once in about 600 years, and is capable of producing earthquakes of about magnitude 7.5. It is this unfortunate coincidence of a large and highly active fault with a major urban area that makes the Wellington Fault Earthquake the earthquake PML for New Zealand.

3. SOURCE MODELS FOR NEAR-BY TSUNAMIGENIC EARTHQUAKES

Four faults in the vicinity of Wellington have significant tsunamigenic potential. They are the Wellington Fault (#7 in Figure 2), Wairarapa Fault, (named), BooBoo Fault (#8) and the subduction zone (#12 and faults to the east of it). The approach used to estimate tsunami losses was to create models of the estimated co-seismic seabed deformation for scenario earthquakes the faults. Elastic dislocation modelling was applied to geometrical models of the fault planes, and, except for the subduction zone sources, assuming a level of slip dictated by the source magnitude and area, and by the fault movement (especially vertical movement) in past events where this was known. In general, the estimated vertical movement from the dislocation model represented the co-seismic surface vertical movement that initiated the tsunami.

Each displacement model was input to a tsunami propagation and inundation model [Neilson & Gray 2005], which was then run for sufficient simulated time to allow the largest waves to reach the major urban locations. From the output of this model the maximum water depths were extracted and used to estimate the tsunami losses using fragility functions.

4. INTEGRATED ELEVATION MODEL

A key to the tsunami modelling is having a seamless elevation model extending from the undersea tsunami sources to the on-land assets at risk. Creation of such a model for the Wellington region and northern parts of the South Island required combining bathymetry and topography data from a variety of sources. This was done in three steps, first the bathymetric model was compiled, second the topographic model, and third the two compilations were merged into one dataset. All of the steps were done in a Geographical Information

Systems (GIS) environment (ArcGIS 9.2). All data was converted to Universal Transverse Mercator projection using the World Geodetic System 1984 Datum which enabled the appropriate input data for the tsunami inundation modelling. The extend of the data was between 42.0°S to 40.5°S and 174.0°E to 176.0°E, covering the localities of interest; Wellington City, Hutt City, Porirua City and Kapiti District. Five nested areas, with varying grid cell size, were provided for running the tsunami animations within the ANUGA software. Wellington, Porirua and Kapiti cities were the inner grids, and the other two were middle and outer grids which covered more areas consecutively.

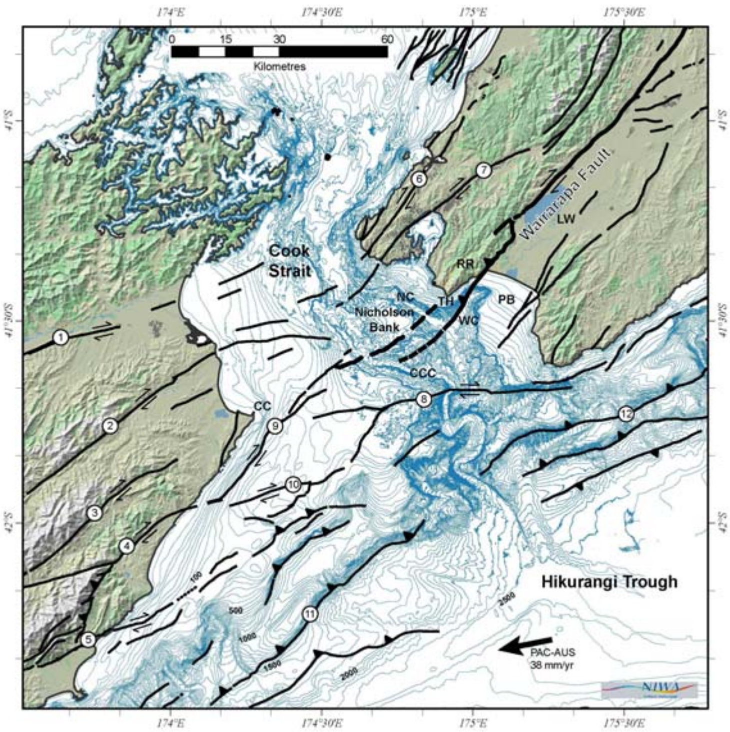

Figure 1: Structure map of the southern Cook Strait region showing major active faults [Barnes 2005].

5. TSUNAMI INUNDATION MODELLING

In order to approximate the effect of a tsunami occurring at high tide, the pre-earthquake water level was everywhere assumed to be 0.5 m above mean sea level (the average tidal range at Wellington being 1m). The elevation data used to apply topography to the mesh were taken from the integrated elevation model. The topography was adjusted to take into account the co-seismic vertical deformations taking place in the simulated earthquake events, and the initial water surface also was determined by the co-seismic vertical motion. It was assumed that the earthquake deformation took place sufficiently quickly that it was effectively instantaneous as far as the water is concerned, and that therefore the water surface mirrored the seabed vertical deformation. The ANUGA model for each source was run for a simulated time of 180 minutes, this being the length of time needed to ensure that maximum water levels were captured especially in locations far from the source, or where resonance effects were important. The maximum water levels reached during the 180 minute period were estimated on a regular 50 meter grid, which formed the basis of the loss modelling.

6. ASSETS MODEL

There are approximately 160,000 residential and 20,000 non-residential buildings in the Wellington Region. Ideally, the location, value and fragility of each one of them would be known, but such a database currently is not available in New Zealand. Instead, a buildings model was developed in which the resolution varied in accordance with the specific need for resolution and the type of data available. The levels of resolution varied from building-by-building to meshblock and area unit. ("Meshblock" and "area unit" are aggregation levels commonly used for statistical purposes in New Zealand. A meshblock is about a city block in size and typically contains 50 houses or 5 non-residential buildings. An area unit is about 10 times larger.) Some of the sources used were building footprint data from local authorities, property valuation data from a New Zealand-wide database and GNS seismic databases. A major disadvantage with the data currently available is the lack of association with other relevant information, like structural and address data. To create the link between the datasets, attributes such as land parcel and property identifier were used as joining parameters and a merged dataset was produced. Attribute relationships were done in GIS and also in excel spreadsheets. The loss calculations were applied to this database The resulting replacement values, in $2007, are summarized in Table 1.

Table 1 Estimated replacement value of buildings in the Wellington Region.

Category	Value ($billion)	Percent of Total
Large Properties	25.3	33
Footprints	42.5	55
Meshblock	9.2	12
Total	77.0	100

7. EARTHQUAKE FRAGILITY AND LOSS

Buildings of the Wellington Region were classified according to fragility, where the major determinants of fragility were the construction type, age, height, and quality of the design (classified as "sound" or "deficient"). By far the dominant type of residential construction in New Zealand is the light timber-frame. Houses of unreinforced masonry construction (URM) are rare, but important because of their relatively very high probability of collapse under earthquake shaking. About 1.5% of the houses in pre-1940 suburbs in Wellington are of URM.

The earthquake loss was obtained from the following formulae:

Loss = Dr x Replacement Value,

where Dr is the fragility function, or "Damage Ratio". It is a function of the intensity of shaking and class of building, and is given by:

Dr = Cost to Repair/Cost to Replace

Damage ratios for low-rise New Zealand buildings have been estimated by Dowrick and co-workers [Dowrick 1991 Dowrick & Rhoades 1993 & 2002, Dowrick et al. 2001]. For loss estimation they are modelled as

$$Dr = A * 10 \exp (B/(MMI-C)) \quad \text{for MMI} \geq 7.0\text{, and}$$

$$Dr = 10 \exp (D * MMI + E) \quad \text{for MMI} < 7.0$$

where Dr is the mean damage ratio, MMI the shaking intensity, and A, B, C, D and E are constants (Figure 3). The functions are based primarily on the New Zealand data for intensities MM5 to MM8 and a combination of New Zealand and United States information for MM8 to MM11 [Cousins 2004, 2005].

8. TSUNAMI FRAGILITY AND LOSS

There is very little data to support fragility functions for tsunami damage, especially for the wooden houses typical of New Zealand. A preliminary set of tsunami fragility functions has been developed, based partly on code design requirements for timber houses in New Zealand and partly on observed damage to timber and reinforced concrete buildings in historical tsunamis, particularly the Java Tsunami of 17th July 2006 [Reese et al, 2007]. A considerable component of judgement had to be used in the derivation.

The New Zealand code for timber houses [Standards New Zealand 2002] specifies minimum wall strengths for resistance to wind and earthquake loadings. After allowing for overstrength (based on judgement) and estimating face loadings due to drag and surge forces from tsunami waves [Camfield 1980], the water depths expected to cause shear failure of New Zealand houses are 2 – 2.5 m (above ground level), for 1 storey buildings and 2.5 – 3.5 m for 2-storey houses. A foundation height of 0.5 m. is assumed.

A note of caution is that it was assumed that the mode of failure is racking of walls of the house, and not collapse of or separation from the foundation. Some older houses do have weak foundations and so it could be possible for them to literally float-away, floor and all, in depths as low as 0.5-1.5 m.

Examples of the resulting tsunami fragility functions are plotted in Figure 2. They are reasonably consistent with data and models described above, and given the variability and sparseness of data there seems little justification for using other than straight line models. Fragility functions for concrete buildings taller than 1 storey were derived by assuming (a) that taller buildings would not collapse under tsunami loading, and (b) that floors above those inundated by water would suffer no damage. Guided by the earthquake code design requirements, fragility functions for two-storey timber buildings were estimated approximately 30% lower than those of 1-storey buildings. There are few timber buildings of more than 2-storeys in New Zealand.

We could find no data to support models of increase in tsunami fragility due to prior earthquake shaking damage, and so we evaluated two arbitrary cases, (a) where a 50% shaking damage ratio is assumed to have caused sufficient structural damage that the tsunami damage ratio also is increased by 50% (note: applied as a factor, so that for example a tsunami damage ratio of 0.2 becomes 0.3), and (b) where a 50% shaking damage ratio results in a doubled tsunami damage ratio. In both cases there is an assumed linear relationship between the increase in tsunami damage ratio and the shaking damage ratio.

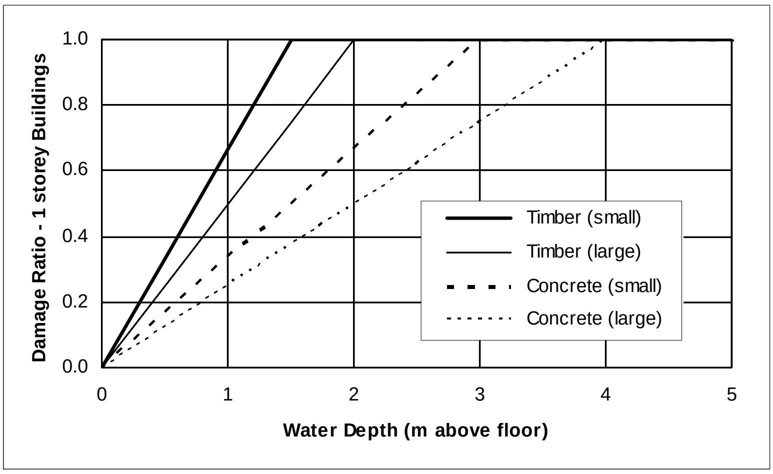

Figure 2: Tsunami fragility functions for low-rise timber and concrete buildings, where a small building is 10 m x 10 m and a large one is 20 m x 20 m.

9. RESULTS AND DISCUSSION

The four main dislocation models have been investigated, one each for the Wellington, Wairarapa and Booboo Faults, and one for the Subduction Zone (called “Subduction to Cook”). Conditions imposed for the initial loss estimates were as follows:

- earthquake microzonation effects present,
- no double counting of earthquake and tsunami losses,
- no increase in tsunami fragility for prior earthquake damage, and
- floor height = 0.5 m above ground for all buildings.

The resulting shaking and tsunami losses, Table 3, indicate clearly that the tsunami losses are negligible for all cases except for the Subduction to Cook model in which the zone of rupture and uplift extends into Cook Strait and the recurrence interval for rupture is 1200 years.

Three important conclusions to be drawn from the results are:

- post-earthquake tsunami does not significantly increase the loss from the Wellington Fault earthquake,
- the second highest loss is due to shaking from the scenario Wairarapa Fault earthquake, for which losses from the post-earthquake tsunami are insignificant, and
- the combined shaking and tsunami loss from the Subduction to Cook event, at $7.9 billion, is comfortably smaller than the Wellington Fault loss of $13.7 billion.

Table 3 Overview of earthquake shaking and tsunami losses. The losses are expressed as both $millions and percentages of the total asset value of $77 billion.

Case	Shaking Loss ($m)	Shaking Loss (%)	Tsunami Loss ($m)	Tsunami Loss (%)
Wellington, mag. 7.5	13,700	17.7	14	0.02
Wairarapa, mag. 8.2	9,200	11.9	4	0.01
BooBoo, mag. 7.4	800	1.1	1	0.00
Subdn to Cook, mag. 8.9, 1200 y RI	6,100	7.9	1,800	2.3

Essentially all of the tsunami losses occurred in the Wellington and Hutt areas (Table 4), with the only exception being a minor loss in Porirua for the Subduction to Cook scenario.

Table 4 Distributions of tsunami losses amongst the four urban locations for the four scenarios.

Case	Tsunami Loss ($m)	Loss Distribution (% of Tsunami Loss)			
		Wellington	Hutt	Porirua	Kapiti
Wellington, mag. 7.5	14	55	45	0	0
Wairarapa, mag. 8.2	4	100	0	0	0
BooBoo, mag. 7.4	1	100	0	0	0
Subdn to Cook, mag. 8.9, 1200 y RI	1,800	77	23	0.01	0

Average loss ratios have been estimated for various broad classifications of the buildings exposed to tsunami damage, i.e. those for which the water depth above the floor was greater than zero, in a Subduction to Cook event. The total "wetted" exposure and estimated loss were $6,000 million and $2,300 million respectively, giving an overall loss ratio of about 0.4. The trends in loss ratio, Table 5, look reasonable. Buildings that are low-rise, residential, or small, have average loss ratios of about 0.6. High-rise buildings have the lowest loss ratio. A significant result is that low-rise buildings (here h <= 2 storeys) account for 95% of the total loss.

Table 5. Loss ratios for various subdivisions of the buildings exposed to tsunami damage.

Category	Condition	Exposure ($m)	Loss ($m)	Loss Ratio
Height (storeys)	h <= 2	4,100	2,200	0.54
	2 < h <= 4	290	76	0.26
	4 < h <= 6	150	10	0.07
	h > 6	1,400	15	0.01
Use	Commercial	1,900	160	0.08
	Industrial	910	270	0.30
	Other	550	230	0.42
	Agricultural	0	0	-
	Residential	2,600	1,600	0.62
Size (sqm)	<=300	2,200	1,400	0.64
	>300	3,800	860	0.23

Given the heavy reliance on judgement in the derivation of some critical parameters, it was deemed advisable to conduct some sensitivity studies, using the "Subduction to Cook" earthquake model because it was the only one giving significant tsunami losses. Conditions imposed for the loss estimates were as follows:

- earthquake microzonation effects present,
- no double counting of earthquake and tsunami losses,
- moderate increase in tsunami fragility for prior earthquake damage.

Some calibration of the above techniques has been possible using historical loss data from New Zealand earthquakes. For large earthquakes affecting many buildings, achieving scenario loss estimates within a factor of two of the truth seems achievable [Cousins 2004]. For small earthquakes affecting relatively low numbers of buildings the individual scenario loss estimates can vary wildly from the truth, but averaging over many such earthquakes, as is achieved by probabilistic modelling, means that the factor of two level of precision is again realistic [Cousins, 2005].

We have no loss data with which to calibrate our tsunami loss methodology, but have compared estimated wave heights from a modelled repeat of the 1855 Wairarapa earthquake with historical wave-runup observations. The model results slightly underestimate the observations in Wellington harbour but this may be due to changes in low-lying topography between 1855 and the present day, or uncertainty in the observations.

In this study, currently available data and techniques were put into a methodology which combined several modelling techniques for estimating the probable maximum loss. Tsunami inundation modelling incorporated selected earthquake and tsunami sources with elastic dislocation models as an input. Also, integrated topography and bathymetry elevation model and surface roughness model in GIS environment provided the elevation and roughness values for the inundation modelling. An attenuation model for earthquake shaking including allowance for shaking conditions were also introduced in the methodology.

The tsunami modelling program ANUGA, produced the water level data which was used to estimate the water depths in the urban areas. These water depths showed the inundation on the land in the GIS environment. Assets model was superimposed to this grid resulting in water depths for the defined assets on land, which linked to the loss calculations done in spreadsheet, using the tsunami fragility functions and estimations. For each defined scenario, this procedure was repeated.

10. CONCLUSIONS

The study considered the joint impact of nearby earthquakes and related tsunami inundation to be considered on the Wellington region of New Zealand. It required a comprehensive topographic and bathymetric model to be developed for the region, including the Wellington harbour and its associated waterfront area. As is common with nearby events, considerable region tilting is to be expected which is known to grossly reconfigure the local terrain. The tsunami modeling undertaken in this study has taken these effects into account when determining inundation effects. During the study it was possible to calibrate one simulation with an actual tsunami event (Wairarapa 1855) with the model results aligning well with observations

The key findings from the study are that the incremental losses incurred from subsequent tsunami inundation of the Wellington region are almost incidental when compared to the losses resulting from earthquake induced shaking damage.

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