Accumulated Losses from Sequences of Earthquakes: Implications for Risk Modeling

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SUMMARY:
We have estimated losses from the seven most damaging events in the sequence of earthquakes that started with the M_W 7.1 Darfield, New Zealand, Earthquake of 3 September 2010. Detailed assets models were developed for the buildings and pipe networks of Christchurch, the city most affected. Residual values were generated for each asset after each earthquake and used as input to the following event. Single event losses for buildings ranged from $NZ 1-5 billion, relatively modest, but they accumulated to nearly $20 billion over the sequence. This total was more than 30% of the initial buildings value of $64 billion. Underground pipes showed similar results. Applying the method to the Wellington Region of New Zealand, where the seismic risk is much higher than for Christchurch, again showed that the total loss over a main-shock/aftershock sequence could greatly exceed the main-shock loss. Implications of this for insurance and reconstruction are discussed.

Keywords: Earthquakes, aftershocks, risks, buildings, pipelines

1. INTRODUCTION

Traditional risk modelling for earthquakes usually involves isolated events, either a single event on a known fault source for a scenario study, or perhaps millions of single events on many sources for probabilistic studies (e.g. Smith 2003). It is relatively rare for linked sequences of earthquakes, like a main-shock followed by aftershocks, to be considered together. In fact, aftershocks are often removed from seismic hazard models as separate entities using a process called declustering, with the energy released by the aftershocks being merged with that of the main-shock (e.g. Stirling et al, 2012).

While merging aftershocks with their main-shocks may be a valid seismological procedure, it is perhaps something that loss-modellers do at their peril. Experiences in the Great East Japan earthquake of March 2011 and the earthquakes around Christchurch, New Zealand, between September 2010 and June 2011 are indicating strongly that it is important to estimate the cumulative damage from aftershocks as well as losses from the main-shocks. In the recent Canterbury (New Zealand) earthquake sequence, for example, damage and casualties due to the main-shock (Darfield Earthquake, 3 September 2010, M_W 7.2) (NZSEE 2010), were eclipsed by those from subsequent aftershocks, in particular a magnitude 6.2 event on 22 February 2011 (Kaiser et al, 2011, NZSEE 2011). Admittedly this was probably a unique situation in that the main-shock was centred approximately 40 km from the centre of New Zealand's second largest city, Christchurch (population about 350,000), whereas the largest aftershocks were almost directly beneath the city (Fig. 1).

The impacts of the aftershocks on Christchurch prompted us to model losses in two earthquake sequences of importance to New Zealand. The first was simply the Canterbury sequence as a calibration exercise, and the second a rupture of the Wellington-Hutt Valley segment of the Wellington Fault. The so-called "Wellington Fault Earthquake" is arguably the most costly earthquake likely to strike New Zealand. It is expected to have a magnitude of 7.5, to involve metre-scale surface rupture through the metropolitan area, and has a likelihood of about 10% in 100 years (Rhoades et al, 2011). Wellington, the capital of New Zealand, is potentially isolated and vulnerable following rupture of the Wellington Fault. It has no significant internal sources of water, food, power, or fuel. All have to be imported either by sea, or through rugged hill country along a small number of vulnerable lifelines many of which will be cut by the fault (Fig. 2). The satellite cities of Lower Hutt, Upper Hutt and Porirua are similarly vulnerable, except that Lower Hutt and Upper Hutt have plentiful access to river and artesian water.

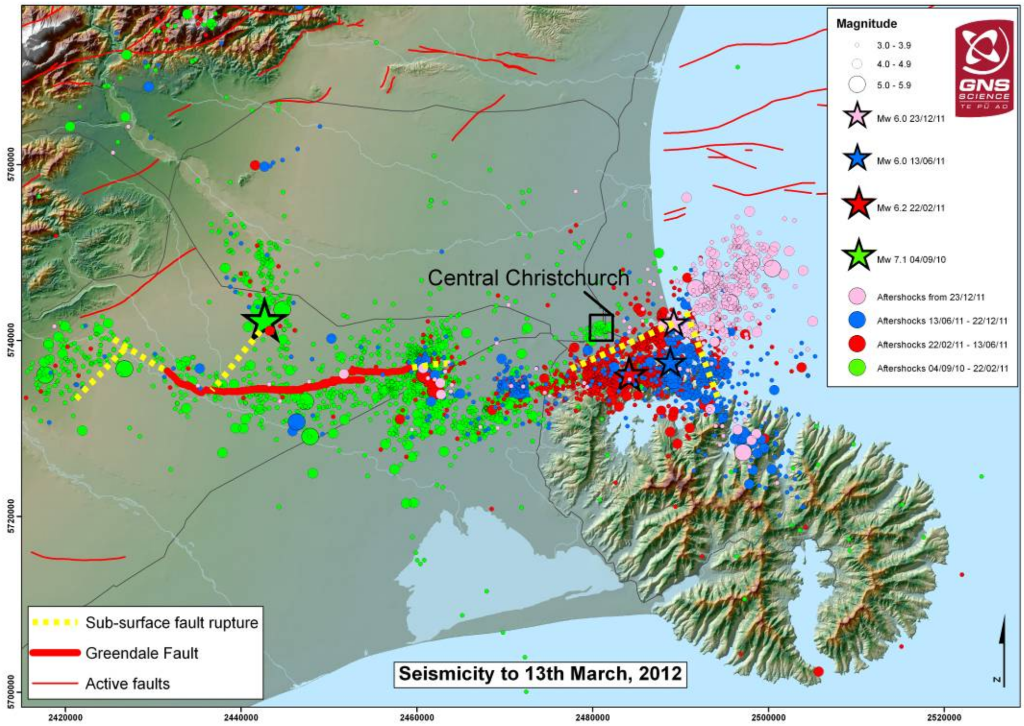

Figure 1. The Canterbury, New Zealand, earthquake sequence, from September 2010 to March 2012 (Langridge, 2012). The sequence has not necessarily finished.

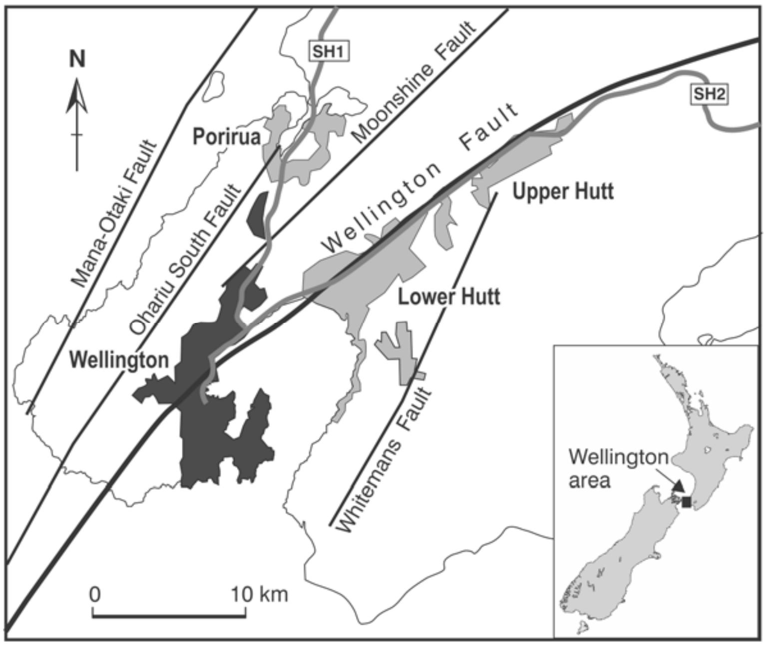

Figure 2. Metropolitan area of central New Zealand with the four main cities, the main active faults and state highways (SH1, SH2). Nearly all of the land around the cities is rugged hill country.

The seismic hazard in the area is high, because Wellington, Lower Hutt and Upper Hutt are bisected by the Wellington Fault, there are four other large active faults within about 15 km, and there is a subduction interface below the cities. The Wellington Fault Earthquake has long been regarded as a worst-case earthquake loss for New Zealand (e.g. Cousins et al, 2009) hence it is of considerable interest to know whether or not aftershocks, or triggered events on nearby faults, could add significantly to the estimated main-shock losses.

2. HAZARD MODELS

2.1. Canterbury Earthquake Sequence

For the Christchurch hazard, we used the seven most damaging events from the Canterbury earthquake sequence of that started with the M_w 7.1 Darfield earthquake of 3 September 2010. Earthquake parameters are listed in Table 2.1, and the locations of the four largest events are shown in Fig. 1.

Table 2.1. Earthquakes that were imposed on the assets of Christchurch.

Event Name	Date & Time (UT)	Moment Magnitude	Distance from CBD (km)(1)
Darfield	2010-09-03 16:35	7.1	22
Christchurch	2011-02-21 23:51	6.2	3
Chch aftershock 1	2011-02-22 00:04	5.6	(6)
Chch aftershock 2	2011-02-22 01:50	5.6	(5)
Chch aftershock 3	2011-06-13 02:20	6.0	(9)
Chch aftershock 4	2011-12-23 00:58	5.8	(14)
Chch aftershock 5	2011-12-23 02:18	6.0	(9)

Note 1: *Distances in brackets are epicentral distances, others are shortest distances to fault.*

2.2. Wellington Earthquake Sequences

Robinson et al (2011) have created a synthetic seismicity model for the Wellington region of New Zealand. It contained the known major active faults of the region (57) plus 3000 sources to represent distributed seismicity, i.e. earthquakes that were not located on the known faults. As a driving force they imposed a plate boundary convergence rate of 42 mm/y, and then as output, created a synthetic catalogue of 500,000 events of magnitude 5 or more. The modelling of stress transfer and resulting aftershock/triggered activity was an important part of the model.

For our modelling Robinson (personal communication 2012) extracted from the catalogue a set of 315 synthetic earthquake sequences, each comprising a Wellington Fault rupture of magnitude 7 or greater followed by aftershocks on the fault and triggered events on nearby faults, all of which were constrained to occur within 3 years of the main-shock, be of magnitude 6 of greater, and located within 10km of the Wellington Fault. The 3-year cut-off time was an arbitrary choice.

2.3. Shaking Model

In order to estimate the expected severity of ground motion (expressed as Modified Mercalli intensity) at any given place, due to a specified earthquake elsewhere, we used the model of Dowrick & Rhoades (2005) which describes the attenuation of MM intensity for New Zealand earthquakes. It takes into account not only the magnitude of the earthquake and its location, but also its focal depth, mechanism and the orientation of the fault source. Natural variability/uncertainty was also incorporated in the attenuation modelling.

3. ASSETS MODELS

We have considered two classes of asset, buildings and underground pipelines, partly because they are the likely sources of greatest losses in earthquakes and partly because suitable assets models were available.

3.1. Buildings

Building-by-building assets models had been developed for Christchurch and the Wellington metropolitan area as part of RiskScape, a risk modelling package being developed jointly by GNS and NIWA (Institute of Geological and Nuclear Sciences, www.gns.cri.nz, and National Institute of Water and Atmosphere, www.niwa.co.nz) (King & Bell, 2009). Attributes attached to each building in the models included the location, replacement value, structural type, age (i.e. era of building code) and quality (with or without structural deficiencies). Ground hazard ratings for shaking amplification, liquefaction and landsliding were also attached. The hazard ratings were taken from GNS's in-house databases. They consisted of five-point ratings for each of the three phenomena, A to E for amplification (paralleling the A (strong rock) to E (very soft soil) ground classifications defined in the New Zealand Loadings Standard (Standards New Zealand, 2004), and 1 (zero hazard) to 5 (very high hazard) for each of liquefaction and landsliding (Dellow et al, 2003, Destegul et al, 2009).

3.2. Pipes

The pipes models consisted of pipe segments with attributes of location, replacement value, diameter, age, quality (brittle to ductile), and the three ground hazard ratings, attached to each pipe segment. There were separate models for water supply, wastewater disposal (sewer) and storm-water disposal systems in recognition of the differing natures and fragilities of each, especially pressure vs. gravity-driven. Note (a) that the modelling involved underground pipes only, which represent only about half of the value of a complete reticulation system, and (b) that the replacement values were arbitrary reasonable values chosen for modelling purposes, and are not to be taken as exact values. The purpose of our work was to examine the relative importance of aftershock losses, not the absolute losses themselves.

4. LOSS MODELLING PROCEDURES

4.1. Buildings

For buildings, the procedure was (i) to select an earthquake main-shock model (magnitude, location, mechanism of rupture), (ii) to estimate the MM intensity at each asset location using the Dowrick and Rhoades (2005) attenuation model, (iii) to adjust the MMI to allow for ground hazards, (iv) to estimate the damage state for each building using damage state vs. MMI curves developed by Spence et al (2008), and finally (v) to estimate the repair cost appropriate for the damage state. Then, the assets model was updated by deduction of the damage costs from the building values, the next earthquake scenario was run, and so on for the full sequence of events. For Christchurch, the event list of Table 1 was run 500 times, and for Wellington each of the 315 synthetic seismicity sequences was run once.

4.2. Pipes

For estimating the damage costs for pipes we adopted a damage ratio method. The procedure was (i) to start with the main-shock earthquake, (ii) to estimate the MM intensity at each asset location using the Dowrick & Rhoades (2005) attenuation model, (iii) to estimate the damage ratio for each pipe segment using fragility functions of the form plotted in Fig. 3, and finally (iv) to estimate the repair costs by multiplying the segment value by the segment damage ratio. Then, the values in the assets model were updated by subtracting the repair costs segment-by-segment, and the above procedure was repeated for the next earthquake in the sequence, and so on. Note that the impacts of the ground hazards were incorporated directly into the fragility functions.

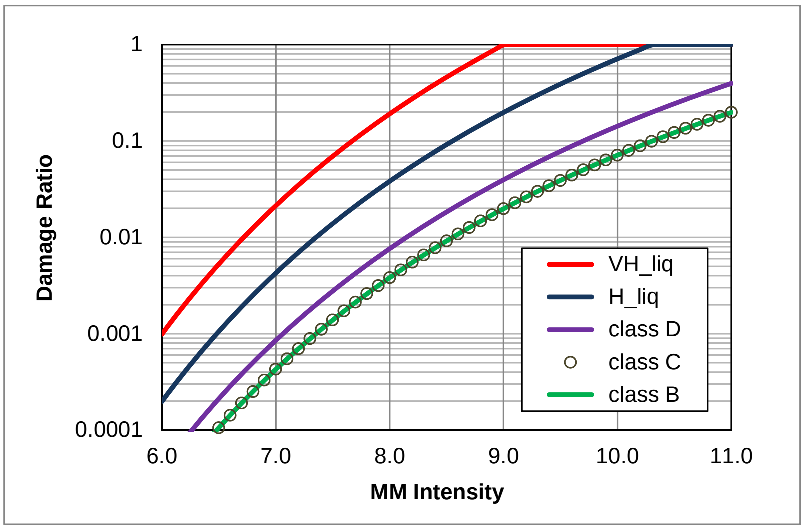

Figure 3. Fragility functions for brittle sewer pipes. Equivalent sets of functions were developed for potable supply, sewer, and storm-water systems, and for ductile, average and brittle pipe types.

5. ESTIMATED LOSSES

5.1. Christchurch Buildings and Pipes

Table 5.1 compares the accumulated losses over the whole sequence with the main-shock (Darfield Earthquake) losses. While the losses in the main-shock event, at approximately 0.5 to 5% of the exposures, were not overly high, the accumulated losses over the sequence of $19 billion for buildings and $280 million for pipes were very high, respectively 30% and 21% of the initial asset values. That is, the sequence losses were more than five times the main-shock losses.

Table 5.1. Median losses for buildings and underground pipe networks, in Christchurch, exposed to the Canterbury earthquake sequence. Results for the pipe networks are presented for all systems together and separately.

Asset Type	Asset ($million)	Main-shock Loss		Sequence Loss		Ratio of losses, Seq./Main
		($million)	(%)	($million)	(%)	
Buildings	63,800	3,400	5.3	19,000	30	5.7
Pipe Systems - together	1,300	38	3.0	280	21	6.8
- Water Supply	400	2.1	0.5	17	4	7.7
- Wastewater	500	24	4.9	160	32	6.7
- Storm-water	400	13	3.2	94	23	7.1

Median losses for each event in the sequence are listed in Table 5.2. As above, the main point to be taken from the results is that while the losses in any particular event were not overly high, most were over half of the main-shock loss and so accumulated to a very high sequence loss. A second point is that the overall building loss is probably not too far from reality, although the final costs of the Canterbury earthquake sequence will not be known for at least a year or two, noting also that the sequence has not necessarily ended.

There appeared to be no significant relationship between the size of the main-shock loss and the accumulated losses in the subsequent aftershocks (Fig. 4).

Table 5.2. Median losses for individual events in the Canterbury earthquake sequence.

Event Name	Magnitude	Christchurch Buildings		Christchurch Pipes	
		Median Loss ($million)	Loss as % of initial Asset Value	Median Loss ($million)	Loss as % of initial Asset Value
Darfield	7.1	3,400	5.3	38	3.0
Christchurch	6.2	4,600	7.2	128	9.9
Chch aftershock 1	5.6	2,300	3.6	14	1.0
Chch aftershock 2	5.6	2,300	3.6	13	1.0
Chch aftershock 3	6.0	2,600	4.0	26	2.0
Chch aftershock 4	5.8	1,600	2.4	3	0.2
Chch aftershock 5	6.0	2,400	3.8	24	1.8

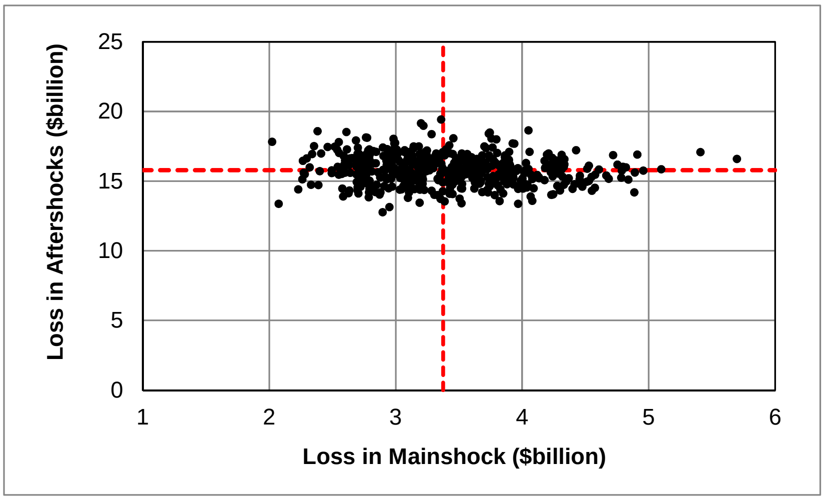

Figure 4. Comparison of main-shock and accumulated aftershock losses, for buildings in Christchurch. The dashed lines indicate median values.

5.2. Wellington Buildings and Pipes

As expected, given that a Wellington Fault rupture results in a magnitude 7.5 earthquake centred on a major metropolitan area, the estimated main-shock losses were high, at 7 to 18% of the exposure (Table 5.3). What was not expected by us was that the accumulated loss over the whole synthetic sequence, for buildings, was double the main-shock loss. However this may be explained by the nature of the sources of the aftershock losses, because the major losses apart from the main-shock loss appear to have been caused not by true after-shocks on the Wellington Fault, but by triggered ruptures of neighbouring faults (Tables 5.4 and 5.5). The triggered events had median magnitudes from 6.5 to 7.2, compared with 6.3 for the Wellington Fault aftershocks, and being within a few kilometres of built-up areas were all capable of generating sizeable losses.

There appeared to be no significant relationship between the size of the main-shock loss and the accumulated losses in the subsequent aftershocks, apart from a not unexpected tendency for the subsequent losses to decrease as the main-shock loss increases (Fig. 5).

An apparently anomalous result was that the total sequence loss for the pipe networks was just 30% greater than the main-shock loss. A probable reason for this is that the pipes model covered just Wellington City, which was strongly shaken in the main-shock event but not so strongly shaken in the mostly more distant aftershocks and triggered events. The buildings model, in contrast, covered all cities of the metropolitan area, and the satellite cities were closer than Wellington to most of the triggered events. Hence the satellite cities, which together almost equal Wellington in value, will have contributed significantly to the later events for the buildings component of the modelling, but not for the pipes component.

Table 5.3. Median losses for Wellington buildings and underground pipe networks – summary.

Asset Type	Asset ($million)	Main-shock Loss		Sequence Loss		Ratio of losses, Seq./Main
		($million)	(%)	($million)	(%)	
Buildings	81,000	14,730	18	29,250	36	2.0
Pipe Systems - together	1,400	164	12	210	15	1.3
- Water Supply	300	22	7	31	10	1.6
- Wastewater	600	77	13	96	16	1.3
- Storm-water	500	68	14	86	17	1.3

Table 5.4. Breakdown of contributions by the main sources to the overall loss (% of loss), numbers of occurrences in the model, and recurrence intervals used in the New Zealand seismic hazard model (RI).

Fault Source	Buildings (%)	Pipes (%)	Occurrences	RI
Wellington (main-shock)	49.6	71.9	315	840
Wellington (after-shock)	7.8	6.8	290	-
Whitemans	10.8	6.4	150	20,000
Ohariu South	8.8	6.2	252	2,500
Subduction Zone	6.7	2.3	718	-
Moonshine	5.6	2.8	121	13,000
All Other Faults	10.7	3.6	778	-
Distributed	<0.01	0.01	239	-

Table 5.5. Median losses for individual events in the Wellington Fault Earthquake sequence.

Fault Source	Magnitudes (16^{th} - 84^{th} percentiles)	Wellington Region Buildings		Wellington City Pipes	
		Median Loss ($million)	Loss as % of initial Asset Value	Median Loss ($million)	Loss as % of initial Asset Value
Wellington (main-shock)	7.5 – 7.6	14,730	18.2	164	11.7
Whitemans	6.7 – 7.3	6,630	8.2	22	1.5
Moonshine	6.2 – 7.3	4,260	5.3	5	0.4
Ohariu South	6.1 – 6.8	2,860	3.5	11	0.8
Mana-Otaki	6.2 – 7.4	2,190	2.7	12	0.9
Wellington (after-shock)	6.0 – 6.6	2,180	2.7	10	0.7

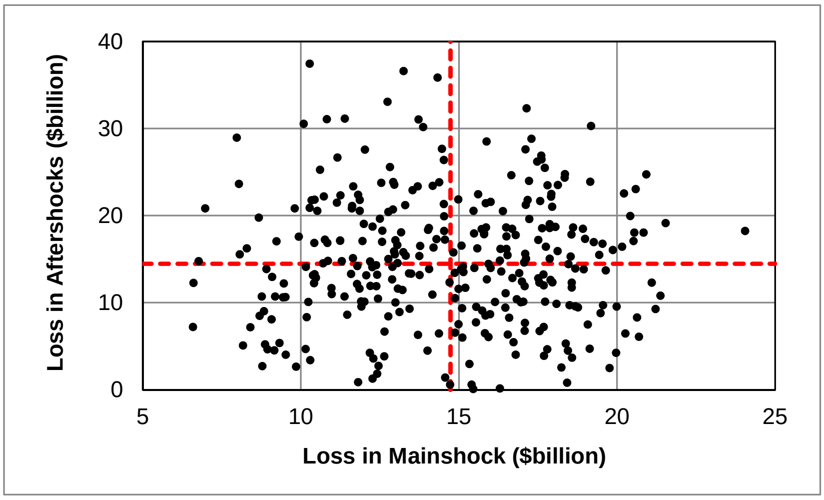

Figure 5. Comparison of main-shock and accumulated aftershock losses, for buildings in the Wellington Region. The dashed lines indicate median values.

6. DISCUSSSION

The Christchurch earthquake sequence illustrates one of those rare situations where the aftershocks cause a higher level of loss than the main-shock. The reason in the case of Christchurch was that the main-shock was at a moderate distance from the city, but then triggered a series of significant aftershocks, magnitude 6.0 – 6.2, that were almost direct hits on the city. Hence the total loss from the sequence was more than five times the main-shock loss. While the main-shock on its own was a significant event it was not a disaster and would have been well within the handling capacity of the emergency responders, insurers and rebuilders. That was not the case for the whole sequence, and the tribulations of Christchurch will have many repercussions for future large disasters in New Zealand, especially for a rupture of the Wellington Fault. A few of the notable problems becoming apparent in Christchurch are (i) many large reinforced-concrete buildings are being demolished rather than repaired, (ii) the start of major reconstruction has been seriously delayed by concerns about the likelihood future large events in the sequence, and (iii) insurance payments have sometimes been delayed by legal discussions about what constitutes a separately insurable event and difficulties in attributing damage to particular events, especially where insurers have changed between events and (iv) funding for additional unforeseen costs of reinstatement for unprecedented events.

The Canterbury earthquake sequence has been the first test in strong shaking of medium to high rise, code-designed, New Zealand buildings. Previously only two medium rise buildings at the Whakatane hospital, both six-storey, had been tested at MM8.0 in the Mw 6.6 Edgecumbe earthquake of 1987 (Pender and Robertson 1987). They performed well. However, fragility functions may have to be updated once final costs from Christchurch are known, because it is becoming apparent that New Zealand’s concrete buildings that have suffered even moderate structural damage may not be economically repairable. They have met their design objective of not collapsing, apart from a few notable and deadly exceptions (Pomonis et al, 2011), but have not met the owner’s expectation of reparability (for which they were not designed). Hence they have been demolished. The full impact of this phenomenon is not yet fully understood. If the Christchurch level of demolition has to be extrapolated to a Wellington Fault Earthquake, in which shaking in the CBDs of the four Wellington area cities is expected to be much stronger than that experienced in Christchurch, then all pre-1976 medium- and high-rise buildings would have to be regarded as total losses and possibly a sizeable proportion of the more modern buildings as well. That would lead to significantly increased loss estimates, and has not included in the modelling reported above.

The largest loss in the Canterbury earthquake sequence was from the earthquake of 22 February 2011, nearly six months after the main-shock, and there was another significant loss in December 2011 fifteen months after the main-shock. A concern is that the most vulnerable areas may be subject to repeated damage so that repairs must either be postponed, or re-done several times increasing the total cost of restoring the assets to full service. Large-scale reconstruction activity involving major buildings appears not to have been achieved in Christchurch, twelve months after the 22 February event. Our hazard modelling for Wellington covered a three-year period from the date of the main-shock. Three years seems an unacceptably long time, but was chosen to reflect both the Christchurch experience and the stronger higher level of damage expected in a Wellington Fault earthquake. Further work needs to be done to determine the probabilities of large after-events as a function of time following the main-shock so that the hiatus in reconstruction can be minimised while not exposing the reconstruction efforts to undue risk.

There could be debate about whether the 22 of February event was an aftershock of the Darfield Earthquake or was a triggered earthquake on a different fault. That would be irrelevant here, because from a risk point of view all that matters is that there has been a sequence of events closely spaced in distance and time. Perhaps the only point of significance for the Wellington earthquake sequences is that the “true” aftershocks, i.e. those located on the Wellington Fault, generally had magnitudes that were at least one magnitude unit smaller than the main-shock, whereas many of the “triggered” events on nearby faults had magnitudes close to that of the main-shock (Table 5.5). Hence, most of the subsequent loss was caused by the triggered events.

A note of caution is, however, that the frequency of occurrence of some of the triggered events does appear rather higher than geological evidence would suggest. Table 5.4 includes the numbers of occurrences of the main loss-causing events in the synthetic sequence, and the recurrence intervals of selected ones taken from the New Zealand seismic hazard model (Stirling et al 2012). Dividing the model duration of 265,000 years ("Occurrences" x "RI" for the Wellington (main-shock)) by the recurrence intervals gives expected occurrences of 13, 106 and 20 respectively for the Whitemans, Ohariu South, and Moonshine faults, compared with the 150, 252 and 121 in the synthetic sequences. Further tuning of the Robinson et al (2011) model seems to be indicated.

The extent of ground deformation liquefaction observed in Christchurch was unprecedented for an earthquake affecting any other urban area in New Zealand. While the modelling has taken some account of damage in very highly liquefiable soils, many of the impacts of lateral spreading, on-going changes in the water table, changes in benchmark levels of the landscape and changes in the profile and capacity of waterways, are yet to be modelled. In this respect the estimates of pipe losses are more robust than those for buildings because the fragility functions were to some extent based on estimates of losses from the Darfield earthquake. However the impact of loss of service on, of example, deep gravity sewerage systems due to loss of gradient even with ductile pipe has not been modelled. Future work to refine this part of the modelling is needed once final buildings losses are known. Fortunately for the Wellington area cities, however, the amount of very-highly liquefiable ground is very much smaller than in Christchurch.

The modelling exercises does not account for demand surge and the additional costs for reinstatement of an asset following a natural disaster. The asset values used in the modelling exercise are for orderly replacement. Some of the additional costs include, but are not limited to, emergency response costs, clean-up costs and removal of debris, temporary repairs to maintain essential services such as water supplies, inspection and investigation costs and other professional fees to design and manage large civil engineering projects. Many of these costs have been muted by insurance policy terms and conditions which impose certain limits or have to be covered by asset owners as they were unforeseen. Other factors not included are possible increases in vulnerability due to damage in prior events, demolitions between events, and repair costs between events where the repair work is undone by a subsequent event. All of the above can be expected to increase the total losses for an earthquake sequence.

As noted earlier, the Wellington Fault earthquake has long been regarded as a good scenario for a worst-case earthquake loss for New Zealand. This status has been maintained even after taking into account possible post-event tsunami for a variety of earthquakes in central New Zealand (Cousins et al, 2009), and adding post-earthquake fire losses increases the dominance of the Wellington Fault event (Cousins and Smith, 2004, Cousins et al, 2012). However, the above results indicate clearly that a Wellington Fault main-shock on its own does not give a worst case loss. It is exceeded both by the accumulated losses from the Canterbury earthquake sequence and the accumulated losses from the modelled Wellington earthquake sequence (Tables 5.1 and 5.3). Given that the Canterbury earthquake sequence is unlikely to recur in the near future (geologically speaking) we suggest that future worst-case modelling for New Zealand should consider the joint occurrence of a Wellington Fault main-shock and triggered events on at least two of the nearby faults.

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