What Can Australia Learn From Christchurch?

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Abstract

The Canterbury earthquake sequence commenced with the Darfield earthquake of September 4th, 2010. The earthquake sequence has been unique in many respects, including the intensity of shaking produced in the Christchurch CBD by each of the major aftershocks in February, June and December 2011. There was widespread damage, including liquefaction over much of the city, rockfall in the hillside suburbs and severe damage to many large buildings, in the CBD in particular.

New Zealand in general is a seismically active zone and Christchurch was considered to be one of the areas of moderate to low seismicity, prior to the earthquake sequence. Although most of Australia is considered a low seismicity zone, the Canterbury earthquake sequence may still offer some insights. It has shown the impact that a relatively low magnitude earthquake can have when it is a 'direct strike'. The long return period of the previously unknown fault may be representative of the possible intra-plate earthquake that could occur practically anywhere.

Building performance can be evaluated, looking separately at preparedness, response and recovery. Observations of building performance, particularly focused on those which were not specifically designed for earthquake, have reinforced that well-configured buildings perform well in short duration earthquakes even when not specifically designed for lateral load resistance. This may be relevant when considering how to deal with seismic hazard in low seismicity zones.

A series of recommendations are made in respect of lessons from Christchurch that may have application to Australia or other low seismicity regions. The recommendations are intended to focus on practical measures to reduce risk and minimise impact, without implementing more widespread specific design measures.

Keywords: Canterbury earthquakes, resilience, preparedness, assessment, recovery, buildings, seismic design.

1 Introduction

This paper provides a brief description and commentary on the Canterbury earthquake sequence and its outcomes, primarily focusing on non-residential buildings. The purpose of the paper is to explore how Australia can learn from the Christchurch experience.

Parallels are drawn between Christchurch and Australia, with consideration of both the underlying seismicity and the built environment. It is evident that there are observations from Christchurch that may provide insights for Australia. The paper considers these from the perspective of preparedness, response and recovery.

Finally, conclusions are drawn, with recommendations for consideration in Australia. These are primarily simple hazard mitigation methods that focus on robustness and regularity rather than specific design requirements.

2 The Earthquakes

The first of the Canterbury earthquakes (the Darfield earthquake) struck at 4:35am on September 4th, 2010. Centred near Darfield, approximately 40km to the west of Christchurch, the M7.1 earthquake caused moderate levels of damage in the city. The epicentre is marked by the green star in Figure 1 below. Maximum shaking intensity of MM9 was observed, but the most severe shaking was in less populated areas.

Five months after the September 4th event, the city was in full recovery mode, although rattled by frequent aftershocks, the most severe of which struck on December 26th, causing some further damage in the CBD. Much repair work was underway, either temporary stabilisation or permanent repairs. A significant number of unreinforced masonry (URM) buildings were closed and cordoned off. Then, on February 22nd 2011, the most damaging earthquake of the sequence struck (the Lyttelton earthquake). The main M6.3 shock (the red star in Figure 1 below) of 12:51pm was centred near Lyttelton, within 10km of the centre of Christchurch, and at only 5km depth. It was followed by four further shocks of M5 or greater within the next four hours, along with numerous smaller events. Shaking intensities of MM9 were felt across the city, with some of the highest ever recorded ground accelerations, in excess of 1.75g lateral and 2.2g vertical in the Port Hills, the region between Christchurch City and Lyttelton.

In total at time of writing, there have been over 10,000 earthquakes in the series. Of these, 52 have been of M5 or greater, with extensive damage at varying levels spread over the five major events, notably on June 13th, 2011 (the blue star), and December 23rd, 2011 (the pink star). Although not as severe in the central city as the Feb 22nd event, the June 13th events in particular caused further damage to the east of the city, including severe rockfall in the seaside suburbs of Redcliffs and Sumner, and still more liquefaction. Figure 1 illustrates the overall spread of the events, with reference to the major events.

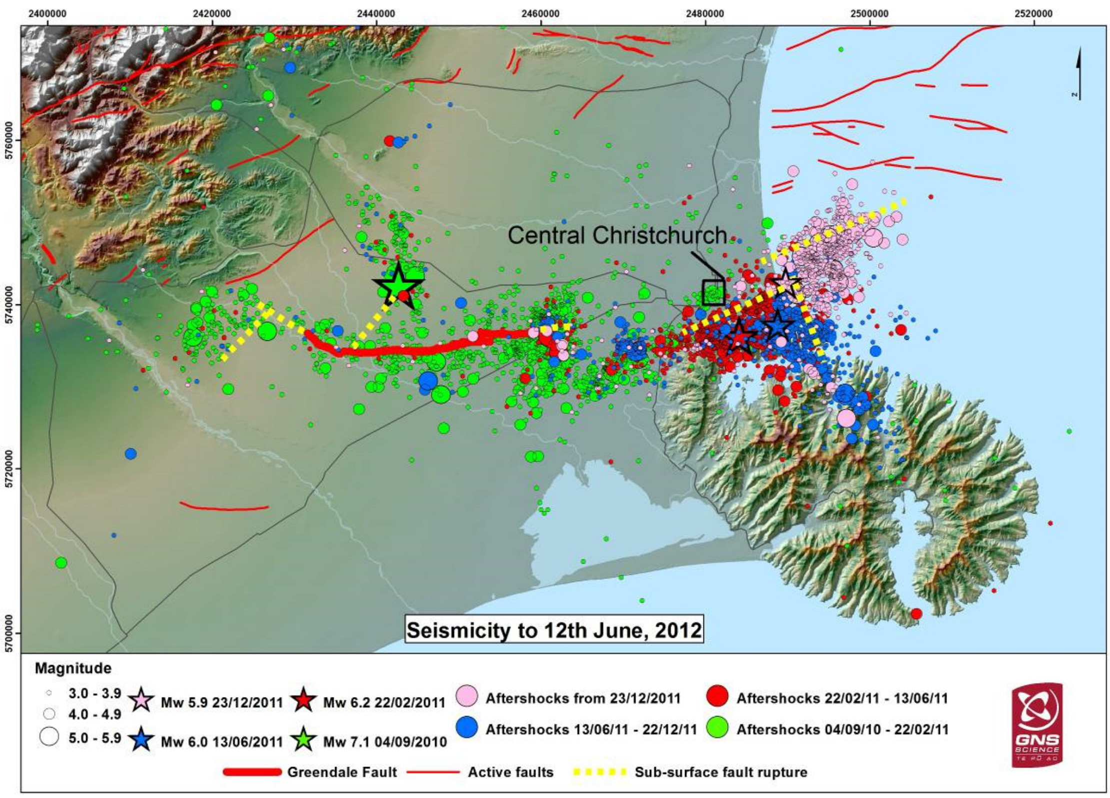

Figure 1. Earthquakes recorded to June 12th 2012 (from GNS Science)

3 Summary of Damage

Following the Darfield earthquake, the most severe damage in the city was to older URM buildings. There were no major collapses, but many URM buildings were severely damaged, and there were a considerable number of such buildings that lost parapets or other ornamentation into the street. In addition, there was a low level of damage to many modern structures, with considerable disruption caused to commerce.

The main concern however was with the liquefaction in many of the residential suburbs, causing widespread damage. Many houses were uninhabitable, and there was widespread disruption to services.

The most damaging event was the Lyttelton earthquake. Damage in Christchurch was extreme, with intensity MM9 shaking throughout the CBD. Two large concrete buildings and a number of masonry buildings collapsed. There were numerous out-of-plane parapet and wall failures in URM buildings, with many of the central city streets rendered impassable due to fallen bricks and other debris. Services were out over most of the eastern and central city and the liquefaction was more severe than in September.

The death toll eventually rose to 185, with 115 deaths occurring in one building, the CTV tower, which collapsed and then burned. Another 18 people died in the PGC building collapse, with a further 42 deaths from building failure, all but one from URM buildings. It is of significance that 37 of the 42 deaths were not in the building that failed, being either in the adjacent building, or in the street. Five people were killed by rockfall in or near the Port Hills.

A detailed review of the performance of the buildings that failed was commissioned by the Department of Building and Housing shortly after the event, leading to the Canterbury Earthquakes Royal Commission that sat through 2011 and 2012. The CERC report[1] was published in seven parts.

Fortunately there were no further deaths in the subsequent events, although the June 13th, 2011 earthquakes led to some near misses, with several engineers and contractors in the act of inspecting already damaged buildings when a second larger earthquake occurred just over an hour after the first.

In aggregate the liquefaction has forced the abandonment of some areas of low-lying land with approximately 7,400 homes being purchased by the Crown. These are the worst of the liquefiable areas, generally alongside watercourses where the land is also subject to lateral spread. The worst of these areas have lost up to 1.5m of elevation due to a combination of liquefaction ejecta (removed) and tectonic movement, leading to concerns of flooding. Conversely, areas of the Port Hills have risen up to 0.5m from tectonic movement.

Well over 100,000 homes have suffered significant damage, with approximately 90,000 being repaired by EQC (under the NZ Government captive insurance scheme) and at least 12,000 further homes that have suffered damage over the cap limit for EQC, that are being repaired by private insurers. About 7,000 people are estimated to have left the city (of a total population of about 350,000), although many have settled nearby and there has been a net increase of about 18,000 in the Canterbury region.[2]

In the CBD alone, it is estimated that up to 1,000 buildings will have been partially or fully demolished, including many of the taller buildings. The central city was cordoned off from the general public from shortly after the earthquake of February 22nd 2011, while demolition was completed and the repairs to the remaining buildings are initiated. Parts of the CBD remained closed to the public until June 28th 2013 and there remain many buildings that are still cordoned off.

The total cost of the earthquake sequence is now estimated as being in excess of NZ$40B. The extent of demolition may have been greater than might have been expected in other countries, due to New Zealand's unusually high levels of insurance cover (approximately 85% of all buildings were covered, compared to more typical levels of 20% or less over much of the rest of the world). Although this will result in considerable external capital being brought into the city, the cost to the city and the country as a whole has been high, and the ongoing disruption will take years to recover.

[1] Canterbury Earthquakes Royal Commission, 2012
[2] Steeman, Christchurch Press 2014

4 How is Christchurch relevant to Australia?

4.1 Geology/nature of earthquakes

Prior to the Canterbury earthquake sequence, it was a common misunderstanding that the principal seismic hazard for Christchurch comes from the Alpine fault. Even now, many lay people are concerned with the potential for the Alpine fault to generate a more severe earthquake in Christchurch than what has already been experienced. In fact, recent research[3] suggests that the maximum horizontal acceleration may be in the order of 0.04 g, which may equate to a building response of about 0.1 g, compared to localized records in excess of 2 g from the February 22nd 2011 earthquake. Significantly however, the duration of shaking associated with an Alpine fault earthquake is likely to be much longer, possibly in excess of three minutes.

The closer faults in the Canterbury plains (for example the Hope and Ashley) are less well-known and will produce earthquakes of lower magnitude. However, the closer proximity to Christchurch will likely generate significantly higher peak ground accelerations, even if the duration is shorter.

Of more relevance to Australia is the source and effect of the Canterbury earthquake sequence, notable for occurring on (mostly) hitherto unknown faults. The local seismicity model included the general Banks Peninsula fault zone, but prior to the earthquake there had been relatively little research into specific faults in this area. Subsequent focus on this area has shown a network of faults, many buried deep under the alluvial plains, marine deposits and within the volcanic deposits that form the Port Hills (remnant from the now extinct Banks Peninsula volcanic activity). The assessed return period for the earthquakes on this fault has been estimated at approximately 10,000 years.

Although the faults in this network are capable of only relatively small magnitude earthquakes, the close proximity of the faults has produced an intensity of shaking rarely experienced in modern cities. The accelerations from the February 22nd 2011 earthquake are among the highest ever recorded. Even though the strong ground motion lasted only for a period of approximately 10 seconds, this earthquake was tremendously destructive as much of its energy was focused on the Christchurch CBD.

An unusual (but not unique) feature of the Canterbury earthquake sequence was that although the first of the series was the largest in magnitude, it was not the most destructive. The aftershock sequence from the September 4th 2010 event was reasonably typical in the decrease in magnitude and frequency of the following events, but the unforeseen aspect was that the aftershocks would progress directly under the city, at shallow depth.

4.2 Low seismicity zones?

Prior to the earthquakes, Christchurch was considered a moderate seismicity zone, in the New Zealand context. Christchurch had a seismic hazard factor, Z=0.22. By comparison, Wellington

[3] Holden and Zhao, GNS 2011

and Auckland have Z=0.45 and Z=0.13, respectively. However, the seismic hazard factor for Auckland has been increased artificially to account for the minimum seismic design actions. The minimum seismic design load for New Zealand is calibrated to the 84th percentile (mean plus 1 standard deviation) ground motion from a magnitude 6.5 earthquake at 20 km radius.

Note that the CBD of Christchurch is approximately 8 km from the epicentre of the February 22nd 2011 earthquake. Areas of the city beyond 20 km suffered comparatively little damage from that event.

Is Australia generally a low seismicity zone? The zoning map of Australia shows only a few zones of higher seismic activity, with the peak seismic hazard factor in Meckering, southwest Australia of Z=0.22, i.e. exactly as Christchurch was. Other areas where seismicity is predicted generally peak at levels closer to that of Auckland. However, the hazard map (to a structural engineer's eye) appears to simply reflect areas of known activity. How much more unknown potential is there that may result in earthquakes similar to Christchurch, also on an unknown fault?

The difficult issue to address is that low seismicity areas are often still capable of generating large earthquakes, although these may have very long return periods. This is the dilemma of contrasting *intra-plate* and *inter-plate* earthquakes. The Canterbury earthquake sequence has been described as *intra-plate*, making it possibly more relevant to the Australian context.

Our codes are typically calibrated to the 1 in 500 year event (with 10% probability of occurrence in 50 years). In areas of low seismicity with long return period events, this results in very low seismic loads, hence the NZ minimum. However if considering the possible extreme event, the differences between areas of low and moderate seismicity are less pronounced. The fact that a fault capable of producing a damaging earthquake has a long recurrence interval is of scant comfort if you happen to be there when it fractures – this is the Christchurch experience.

The philosophical question to be considered is whether building codes should require design for life safety in the design earthquake (nominally the 500 year event), or with consideration of collapse prevention in the maximum considered (or credible) earthquake (MCE). The former is generally the case in New Zealand where the relativity of the two is such that collapse prevention in the MCE can generally be assured by designing for life safety under the design earthquake. But in low seismicity zones, this may not be the case. This may not require rethinking of the design process, but could be addressed instead by simple detailing.

4.3 Building Stock

Christchurch was settled from the 1840's, mostly by people of English origin. Built around the slow-moving Avon River, Christchurch was known as an English city and retained the greatest proportion of early (mostly gothic) stone buildings of all cities in New Zealand. It had also retained a large population of brick buildings dating from the late 1800's through to the early 1930's (when unreinforced masonry was banned following the 1931 Napier earthquake).

Many of the brick buildings had been at least secured – that is, the walls and parapets had been tied back to the floors and roof. A small proportion had been seismically strengthened to a higher level, some as high as 67-75% of (then) current code. However, despite legislation encouraging owners to upgrade, many remained unimproved.

In addition there was a great number of non-ductile concrete frame and wall structures that pre-date modern seismic-resisting design codes (introduced in the mid-70's). These were typically in the two to three storey range. Most but not all of the medium and high-rise buildings were constructed since 1976.

The older unimproved buildings in particular offer significant insight to low-seismicity regions as observations of their performance provide an insight into the potential risk factors that may affect the resilience of cities in low-seismicity regions.

5 Adding Resilience to our Communities

Resilience is a community issue – it is not restricted to engineers, buildings and lifelines. Nor is it solely the preserve of earthquake specialists. There are many views as to what resilience really means, but there is a general theme – that of the capacity of individuals and communities to survive, adapt and grow, no matter what the circumstances.

To revert to the structural engineering context, we may consider the three basic phases of preparedness, response and recovery in considering ways to increase resilience.

5.1 Preparedness

5.1.1 Regulation and Policy

One of the often forgotten facts of the Canterbury earthquake sequence is that there were many buildings already closed and cordoned off pending evaluation and repair at the time of the February 22nd 2011 earthquake. Had that not been the case, many more people may have been killed by masonry buildings than the 42 otherwise attributed to masonry in the February earthquake. In evidence to the Royal Commission[4], it was suggested that 300 more people may have died without those building closures.

An issue that emerged following the first earthquake was the gap in legislation dealing with damaged buildings. The Building Act sets in place regulations to require strengthening of the most at-risk buildings (although this legislation is under review) and to ensure new buildings are of an adequate standard. The Civil Defence and Emergency Management Act places powers in the hands of a Controller with powers to enforce safety standards.

However, there remains no legal means of ensuring that in the post-emergency phase, the safety placards assigned to buildings would remain in place and that building owners would identify and repair damage which could be dangerous if unaddressed. Such buildings could eventually be

[4] Ingham JM, to the Canterbury Earthquakes Royal Commission

declared ‘dangerous’ under the Building Act, but this process takes considerable time and administrative resource to implement on one building, let alone many. A review of the interaction of the various legislative mechanisms is underway, aimed at ensuring the survival of the placards and hopefully, adding measures to enable further review.

A review of applicable legislation is recommended in any area which may be prone to damaging earthquakes or other disaster, to ensure that emergency management procedures integrate effectively over time with ‘business as usual’. Local authorities need to be able to continue placarding and review processes after emergency restriction are lifted, if the severity of the event demands it.

5.1.2 Buildings

In general, buildings performed reasonably well given the extreme loadings experienced in the CBD, with only a few exceptions. However, the extent of subsequent demolition has caught many people by surprise, including structural engineers. Part of this could be put down to the high level of insurance with favourable terms, but there are other lessons to be learned about the performance of buildings.

Unreinforced Masonry Buildings

Engineers have long been aware of the potential benefits of seismic retrofit measures, particularly in the case of the most dangerous unreinforced masonry buildings. However, this has been difficult to justify economically even in regions of high seismicity. The previous low incidence of earthquakes in urban areas, the ready availability of insurance and the expense of retrofit had combined in Christchurch to result in (arguably) a high level of complacency.

The NZ Building Act defined earthquake prone buildings, but left it to individual Territorial Authorities to set their own policies. In the case of Christchurch, this resulted in a passive policy. That is, owners would only be required to assess and upgrade poor buildings if applying for a building consent for other work. The outcome of this was that there was a significant proportion of unreinforced masonry buildings with little or no seismic retrofitting.

It is worthwhile to consider the performance of these buildings. The data gathered from building surveys since the earthquakes are yet to be fully analysed and may never yield a full picture of the damage distribution. However, there are a number of subjective conclusions that can be reached, based on observation:

1. One of the most important and perhaps obvious conclusions, is that having complete and simple load paths is considerably more important than pure strength. Many older unreinforced masonry buildings that had low capacities performed well. In the most extreme cases, buildings that were clearly earthquake prone (by current standards) but had complete load paths and adequate redundancy, achieved levels of performance consistent with new building life safety objectives. That is, occupants were not at risk.

This was probably in part due to the short duration, which is likely to be a feature of the type of earthquake that may be expected in Australia also.

2. Another interesting observation with respect to unreinforced masonry buildings is that there were relatively few in-plane failures, even in those buildings that had weak shopfronts. However, out-of-plane failure was common, even where there had been securing worked completed (some of which dated back to the 70's and 80's). Punching failure at the ties was common even with external plate washers (as opposed to epoxied anchors). This observation, in part, is likely to lead to a simplified approach for dealing with small, regular URM buildings that may be equally applicable in Australia. Essentially, the spacing of the ties should be a function of the wall thickness, rather than based on assessed demand at low seismic load that may have no relevance to an actual earthquake.

3. The influence of the geotechnical conditions was perhaps greater than anticipated. Even compared between sites without significant liquefaction, it was clear the buildings on 'better' founding conditions fared considerably better than those on poorer ground. This was less to do with the amplification effects of soft soil, and more with the additional imposed differential settlement compounding the effects of seismic displacement. This is critical for brittle buildings.

Concrete Buildings

Since the 1931 Napier earthquake, most large scale development in New Zealand has consisted of reinforced concrete (RC) structures. This has been due mainly to imported steel costs and the ready availability of the raw materials required to manufacture concrete. Significant improvements were made to RC structures with the advent of seismic design as we now think of it in the 70's. The Christchurch earthquakes represented the first true test of these design methods.

Results were mixed. On one hand, it was evident that buildings that were properly designed and detailed to comply in full, all behaved as they should have. There are a few amendments to the Standards that are being contemplated as a result of observations of particular issues, principally in the detailing and minimum reinforcement provisions for shear wall systems, but on the whole, life safety objectives were achieved.

On the other hand, the earthquakes highlighted some areas of concern for further consideration:

1. There were a surprising number of buildings that, with hindsight, did not comply with the Standard of the day. The CTV building was the most notable of these, but there were others, including buildings that were either recently completed, or even under construction. This relates to both design and construction. Future consideration is being given both to the quality of the work being completed by design engineers and to the levels of regulatory review given to building consent applications.

2. Construction review also requires significant attention. Acknowledging that it is not generally possible for the design engineer to be permanently on site and that the clerk of works role has long gone, it is clear that more consideration should be given to the construction of critical building elements.

   One possible way of achieving this is the 'Special Inspector' role as used in North America. Under this system, a list of critical elements is defined in the Building Code and may be added to by the designer. These elements are then subject to supervision and testing by an independent inspector engaged directly by the owner.

3. Despite the assumption that ductile RC buildings would be repairable following significant earthquakes, that has often not been the case. While much of this may be attributable to insurance processes, there are now significant concerns over the effects of strain hardening, strain aging and low cycle fatigue. This is a significant research concern and may lead to a re-evaluation of how much ductility demand we should be designing our buildings for, although the detailing provisions should not be relaxed.

4. New Zealand's predilection for the use of structural precast concrete has potentially resulted in much greater levels of damage than might have been expected from similar cast insitu RC buildings. Much of this relates to the fragility of our floor diaphragms under the effects of plastic hinge elongation and to the behaviour of splices and other connections.

5. In common with the URM buildings, many older buildings that predated modern seismic design provisions performed well when they were regular structures with simple, clear load paths; and were founded on good ground.

Other Building Issues

Some more general observations may be made that apply regardless of material or building type:

1. Many buildings may not have performed as well as expected because of stiffness incompatibility of the lateral and gravity load resisting systems. This more commonly applied to strengthened buildings where the strengthening systems were not able to resist load until the building had substantially failed. Of more concern were the few more modern buildings where this happened. This illustrated the need to assess the possible effects of non-linear displacement in buildings with ductile systems. Until the mid to late 90s, it was not common to model the full building structure due to lack of adequate computers. Now the full structure is routinely modelled, which may result in a reduction in overall strength (as the gravity system capacity will be discounted from the demand) but will allow a better assessment of compatibility.

2. In the long run, the easiest and most cost-effective way of upgrading our building stock is simply to design and construct better new buildings. While it may be practical to simply increase seismic design loads and detailing requirement in high-seismicity areas, it is

difficult to justify this for low-seismicity zones. However, the performance of well-configured regular buildings may provide some food for thought.

Consideration could be given to providing simple robust detailing provisions with minimal specific seismic design that could apply to buildings meeting configuration and regularity provisions, with specific seismic design reserved for those buildings that did not meet these provisions.

3. Many heritage buildings had not been strengthened due to concerns over the intrusion of the proposed strengthening systems, despite some having been through extensive studies in the years prior to the earthquakes. Some such buildings are still with us, but many were severely damaged and some were destroyed. The most precious may be rebuilt, but they will never be the same from a heritage perspective. With a little more pragmatism, more of our heritage would have been protected.

   Heritage is a societal issue – while those buildings that are in public ownership may be allocated funds and upgraded, those that are in private ownership are often regarded as a liability. If, as a whole, society wishes to retain these buildings, we need to consider ways to make funds available. But equally, we must recognise that not all such building may be saved, and should prioritise to save the most significant.

4. A number of interim measures were recommended by the Structural Engineering Society (SESOC)[5], recognising that changes to the Building Code would take much longer to implement and some immediate guidance would reduce the risk of replacement buildings becoming non-compliant shortly after construction. This reflects the need to recognise and communicate shortcomings in design practice as soon as possible, in order to minimise impact on the recovery.

5.2 Response

The Christchurch earthquakes presented a first opportunity to deploy the NZSEE Rapid Safety Evaluation guidelines[6]. This document had been recently written but the planned training sessions had not been undertaken and relatively few engineers had previous experience of post-earthquake building damage evaluation.

Subsequent studies[7] have addressed this in more detail, but there were considerable learnings from the assessment process. Some of the key findings were:

1. Training is required for engineers who may be expected to carry out these evaluations. It was increasingly obvious through the earthquake sequence that quality and consistency improved with fewer, more experienced engineers completing the evaluations. With so few earthquakes to increase consciousness of the need, it is likely that the best approach

[5] Various, SESOC, 2013
[6] NZSEE, 2009
[7] Galloway & Hare, NZSEE 2012

for Australia may be to concentrate on building a relatively small core of well-trained engineers, rather than try and spread it far and wide.

2. The need to protect the public through building closures and cordons must be balanced against the need to resume normal commerce, including restoring street access. With hindsight, there were a number of instances where this could have been better managed in Christchurch, particularly after the first earthquakes, leading up the February 22nd 2011 event. In particular, assessment of possible aftershock activity and communication of risk are vital.

3. It is important to have a consistent means of evaluating buildings in order to ensure that critical and sometimes hidden damage is identified, and that its impact is considered. This may inform whether continued occupation prior to repair is appropriate.

   The Engineering Advisory Group (EAG) appointed by the Ministry of Business, Innovation and Employment (MBIE) assumed responsibility for the preparation of guidelines shortly after the February 22nd earthquake. To enable early publication and distribution, the Structural Engineering Society hosted Canterbury-specific guidelines[8] on their website. In the longer term, a national version is likely to be published by MBIE.

5.3 Recovery

The recovery is now in full swing. The scale of destruction and subsequent demolition have been devastating, but not necessarily typical.

It is likely that the unusually high proportion of properties that were covered by earthquake insurance (by international standards) was a contributory factor to many of the demolitions. Although this is balanced by the influx of insurance settlement money, only time will tell whether this is the better outcome. It is likely that insurance policies in the future will have considerably tighter terms that will limit the extent of future large scale demolitions.

Conversely, the removal and replacement of buildings that may otherwise have languished through years of indecision and dereliction may prove to be a positive outcome. By creating a compressed CBD, planners hope to achieve a vibrant core for the city that was previously lacking. This will depend in part on the quality of the replacement buildings, but early signs are promising.

Although to many the recovery cannot happen fast enough, a measured approach is vital. Balance must be struck between flooding the city with short-term personnel (both technical and labour) with no vested interest in the outcome and under-resourcing. Inflation of building costs is significant, as expected. The extent of the city's horizontal infrastructure replacement continues to choke transportation routes, adding further delay and frustrations.

[8] Engineering Advisory Group, 2011.

The Christchurch City Council is facing significant shortfalls and is struggling to meet its commitments. The government anticipated this and responded by creating the Canterbury Earthquakes Recovery Authority (CERA). CERA has accomplished much, but the relationship with the CCC has been strained at times and there has been a sense that more decisive leadership from CERA at key times could have facilitated the early stages of the recovery.

It will be some years before the quality of the recovery can be fully evaluated. In the meantime, it is consuming much of the engineering and construction resource of the country.

6 Summary and Conclusions

There are significant issues to be faced when addressing seismic hazard in low seismicity zones. The highly infrequent occurrence of significant earthquakes further skews the benefit/cost ratio to the level that makes it theoretically impossible to justify any seismic design. However, Christchurch experience has shown that a direct hit from even a moderate earthquake can be devastating and that the unforeseen costs quickly mount.

The Christchurch earthquakes also showed that there may be significant steps that can be taken to provide greater protection for relatively little cost (compared to full seismic upgrade programmes). Some recommendations for consideration include:

1. For regular unreinforced masonry buildings of up to three storeys, a non-specific design programme of simple retrofits comprising upgraded, closely spaced connections to floor and roof diaphragms could achieve significant increase in safety.

2. For non-ductile concrete buildings, identification and retrofit of the worst configurations and details may prevent large-scale losses such as the CTV and PGC buildings. However, it is unlikely that a more extensive retrofit programme could be justified.

3. Although most of the country may be considered of low seismicity, there remains the possibility that an earthquake of similar scale to that experienced by Christchurch could happen just about anywhere. Given the low probability of a direct hit on a populated area, it would be uneconomic to require specific seismic design to a level that is reflected even in the lowest seismic zones of New Zealand. However, the introduction of specific design and detailing provisions for buildings that fail to satisfy configuration requirements, together with more widespread non-specific robustness provisions, may be considered. This could suppress the worst of the behaviour observed in buildings in Christchurch.

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