Technical Note

Lessons from the February 2011 M6.3 Christchurch Earthquake

Gregory A. MacRae

Associate Professor, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, e-mail: gregory.macrae@canterbury.ac.nz

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ABSTRACT

A magnitude 6.3 earthquake struck Christchurch, New Zealand at 12:55 pm on 22nd February 2011 resulting in liquefaction, rockfall and shaking induced building damage. The peak horizontal ground acceleration of 1.68 g was much higher than the design level of 0.22 g and it is much greater than that recorded in most other earthquakes around the world. The severity of shaking was due to the fault proximity to Christchurch, the fault rupture mode and local site effects/conditions. The death toll was 185 mainly due to building collapse. Backgrounds to a number of post-earthquake decisions are described. These relate to: the level of shaking to be considered in future Christchurch building designs; earthquake-prone buildings; University of Canterbury reactions; governmental response; engineering community activities; insurance company issues; and decisions by citizens affected by earthquake damage. Major lessons learnt relate to the effects of severe earthquake shaking, ground deformation and aftershocks on loss and recovery, the need to develop better assessment and repair methodologies, and the need to develop buildings which will sustain much less damage in future earthquake events.

Keywords:
Earthquake sequence; Lessons learnt; Christchurch earthquake

1. Introduction

On the 4th of September 2010, a M7.1 earthquake sourced at Darfield, Canterbury caused considerable damage and loss to Christchurch and its surrounding suburbs. Severe damage was incurred on some unreinforced masonry (URM) buildings, some houses in the region of high shaking, and on buildings/ houses on liquefiable soil over a large region. The shaking and the effects were summarized by MacRae [1].

Subsequently, many earthquake aftershocks occurred in a period exceeding 2 years. One of them, a M6.3 earthquake occurred on 22nd February 2011 at 12:55 pm. This caused significant damage and life loss. A comparison between the ground motions recorded in the two earthquakes in a station in central Christchurch is presented in Figure (1). Although the earthquake magnitude was smaller, the shaking observed in the central Christchurch and in its south-eastern suburbs was much greater than those from the M7.1 earthquake. Based on discussions with Paul Somerville and John Berrill, there are a number of reasons for this:

1. The earthquake hypocentre and rupture was located much closer to Christchurch than in the 2010 M7.1 earthquake. The depth to the hypocentre was about 5km.
2. There was a near fault directivity effect. The shaking was focussed up toward Christchurch and Lyttleton. The steeply dipping surface generated shear waves with a strong vertical component.
3. There was a hill crest effect shown in Figure (2) causing focussing of shaking near the crest. It focuses in places and cancels out in other places giving variable shaking. Because the hill is hard rock, it provides little opportunity for attenuation of the high frequency components.

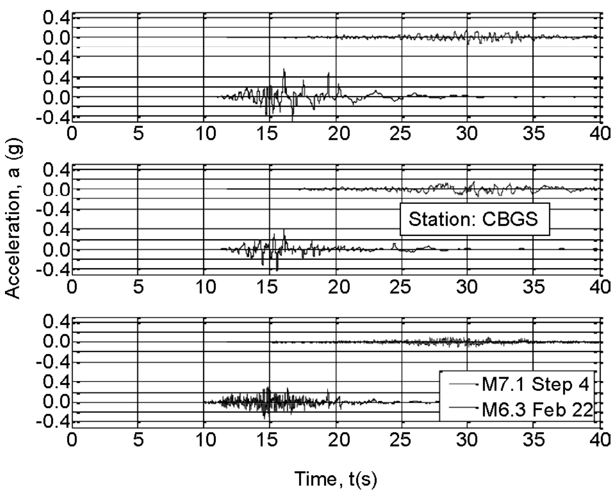

Figure 1. Christchurch Botanical Gardens records (from Brendon Bradley, U. Canterbury, New Zealand, based on GNS data).

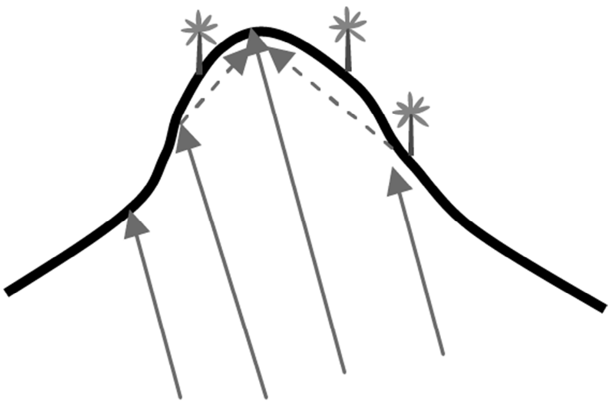

Figure 2. Ridge effect (Focussing of rays).

4. There was a trampoline effect caused by the strong vertical shaking moving down and up again throwing the soil, structure or contents into the air.
5. There was a basin effect near Christchurch as the waves moved between the different layers of soil. According to Berrill [2], the same energy causes greater deformations in the softer basin soils than in the stiffer soils. In Christchurch, the main layers are:
   - The full depth of the alluvial gravel deposits of 700-1000m, which has a horizontal period of resonance of about 2.5-3.0s.
   - The upper 10-30m of very soft soil, laid down loosely in the rapid sea-level rise following the last glaciation about 10,000 years ago. The resonant period of this layer varies markedly depending on its thickness and density, but is in the range of 0.5-1.0s.
6. There was a hanging wall effect, which amplifies the high frequency shaking. This is illustrated in Figure (3) and it affected the structures on the hills [2]. Here, waves are reflected back to the surface by the fault. Energy gets trapped in the hanging wedge/wall and reflected waves can be combined with direct waves (not shown) to obtain very strong shaking at a site.

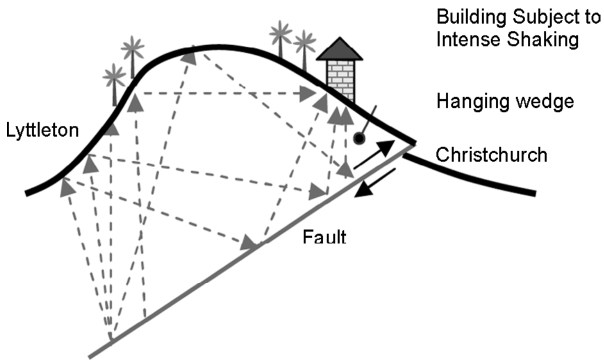

Figure 3. Hanging wall/wedge effect (From Berrill [2]).

7. The rupture was subsurface. These ruptures which don't break the surface may have significantly stronger shaking than those that do break the surface according to Somerville [3] based on observations from previous earthquakes.

It is not clear in the Canterbury earthquakes whether or not there was a basin edge effect which focuses longer period waves from a number of angles to specific area just inside the edge of the basin.

There was considerable discussion about whether or not the M6.3 shaking was an earthquake in its own right, or whether it was an aftershock which was part of the earthquake sequence. According to GNS Science, an aftershock rupture must be both close in terms of proximity and time to the main shock rupture. In addition, it must be of lower magnitude than the main shock rupture. The M6.3 rupture satisfied all three criteria, as it occurred near the end of the M7.1 rupture fault, and it was close in time being about 5 months after the main shock, which is less than the 2-3 years expected for a M7.1 rupture [4].

The location of the 2011 M6.3 fault is shown by the yellow line in Figure (4) while that of the 2010 M7.1 fault is shown by the red line. It should be noted that the fault lines do not meet up, so investigations have been undertaken by geologists and seismologists about the possibility of a further

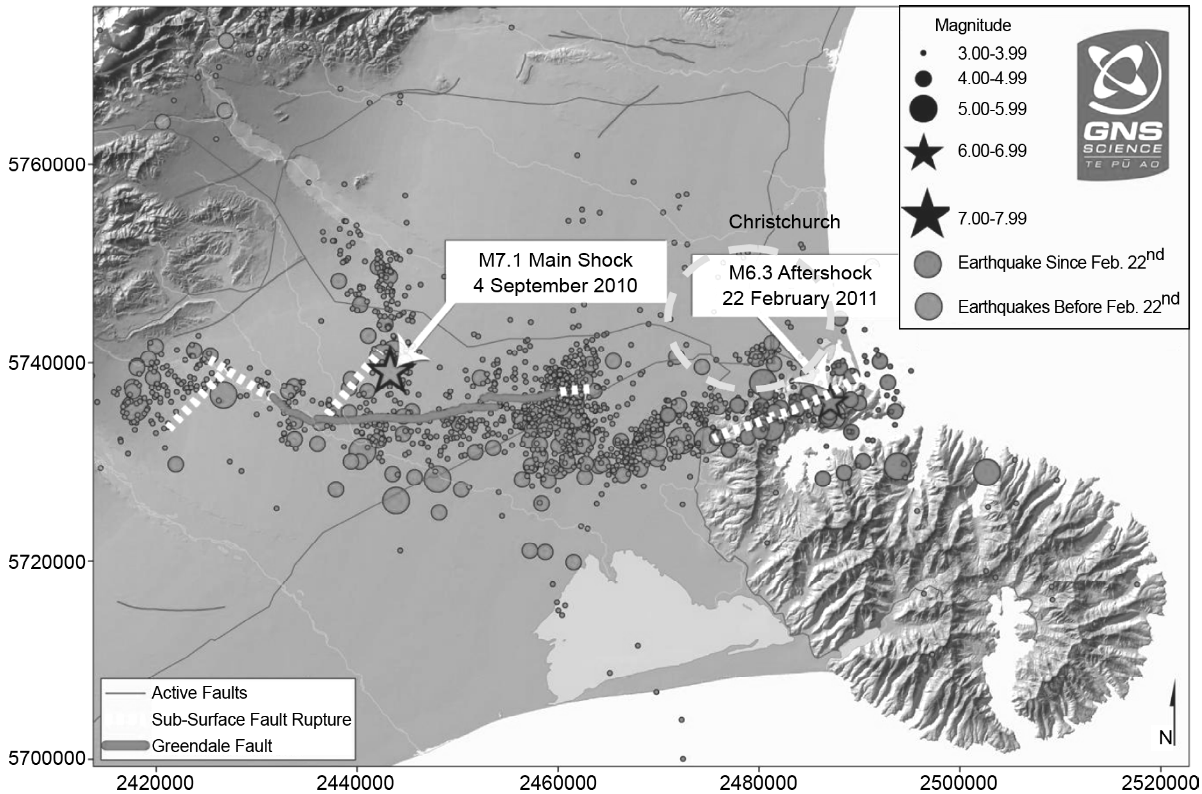

Figure 4. Approximate fault and aftershock locations (Modified from GNS Science).

aftershock there, or from a fault beneath Christchurch.

The response spectra of ground motions recorded at some CBD (central business district) sites are compared with the design spectra in Figure (5). The dashed black line is the 500 year design spectra, while the solid black line is 1.8 times this value. This is nominally considered to be the maximum credible earthquake (MCE). It may be seen that the CBD shaking was often considerably greater than both of these curves; often significantly more than 2 times the design level. There is also a hump in the response spectra at a period of about 3 s, which is consistent with the basin effect described in point 5 above. In a design level earthquake we generally expect structures to be damaged to a repairable extent so that they can be reused, whereas in an MCE event (close to the levels of shaking that were experienced) we generally hope that structures may be severely damaged but do not collapse so that life is preserved.

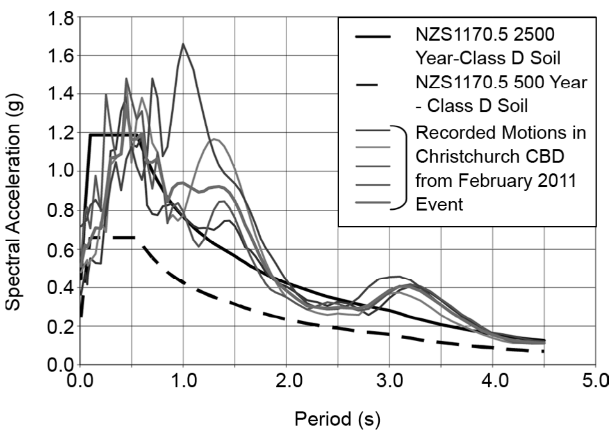

Figure 5. 22 February 2011 M6.3 earthquake response spectra (Courtesy Geonet).

One of the largest levels of shaking occurred at a school in a valley beside the port hills as shown in Figure 6. The two horizontal components of ground acceleration were very high with the PGA (peak ground acceleration) of 1.68 g and 1.27 g, respectively. According to Berrill [2], for about 20 years the strongest horizontal peak acceleration recorded was the 1.25 g from Pacoima Dam, in the epicentral region of the 1971, M6.4 San Fernando earthquake in northern Los Angeles. It indicates that the shaking was very strong. The vertical accelerations were very high in the positive direction but close to 1 g in the negative direction. The peak downward (negative) acceleration will likely occur when the instrument is at the peak upward displacement. A value of 1.0 g indicates that the equipment, the slab, and the building was probably lifted up in the air and separated from the ground. When it came down it bounced on the ground causing impact with the soil and the positive accelerations shown. It is similar to the behaviour of a person bouncing on a hard trampoline. On hills close to this school, some large rocks rolled and bounced down the hill into residential houses. There was also some damage at the school itself, with masonry walls in 2 buildings which had moved, and an unreinforced masonry heating building and chimney that had come down. Apart from that, the school buildings looked to be unaffected.

2. Damage

The damage observed in the 2010 earthquake included liquefaction damage to houses, chimney damage to houses, and collapse of older URM structures. There was also significant liquefaction and lateral spreading over a wide region. In the 2011 event, these effects were magnified over a smaller geographic region. Some notable features were:

1. Houses on the hills spurs were in some cases shaken to bits. That is, the bricks and veneers came off, and the internal linings were so much cracked that they provided no strength. Only the framing, which could sustain significantly greater displacements than the rest of the internal and external cladding remained relatively undamaged.
2. Houses on the side of hills often had some foundation movement and cracking, thereby distorting the house.
3. Many houses at the bottoms of slopes were bombarded by rocks which had been resting on the hillsides above them.
4. Cliffs near houses often gave way, sometimes throwing large boulders, or rocks onto buildings below. A number of people died as a result of this. Also, the cracks at the top of the cliffs meant that many houses were considered too risky to be inhabited.
5. As land deformation occurred on the hillsides, and as cracks opened, it often broke underground pipes. The water/liquid flowing from these broken pipes as well as rain water increased the chance of further sliding induced damage.
6. The scale of damage to historic URM buildings, like Christchurch Cathedral, and other heritage structures was much more severe in this earthquake. Some of these buildings (and their parts) collapsed onto cars or buses underneath in the street killing people. Older URM buildings retrofitted to 33% of the current code demand, which were still brittle, behaved poorly with major collapses under the levels of shaking experienced, see Figure (6).
7. Industrial buildings fared relatively well, but in a number of tilt-slab structures, the steel connections (particularly the welded ones) performed poorly.
8. Most of the central business district consisted of reinforced concrete buildings (apart from old URM buildings). From about 1975, buildings in

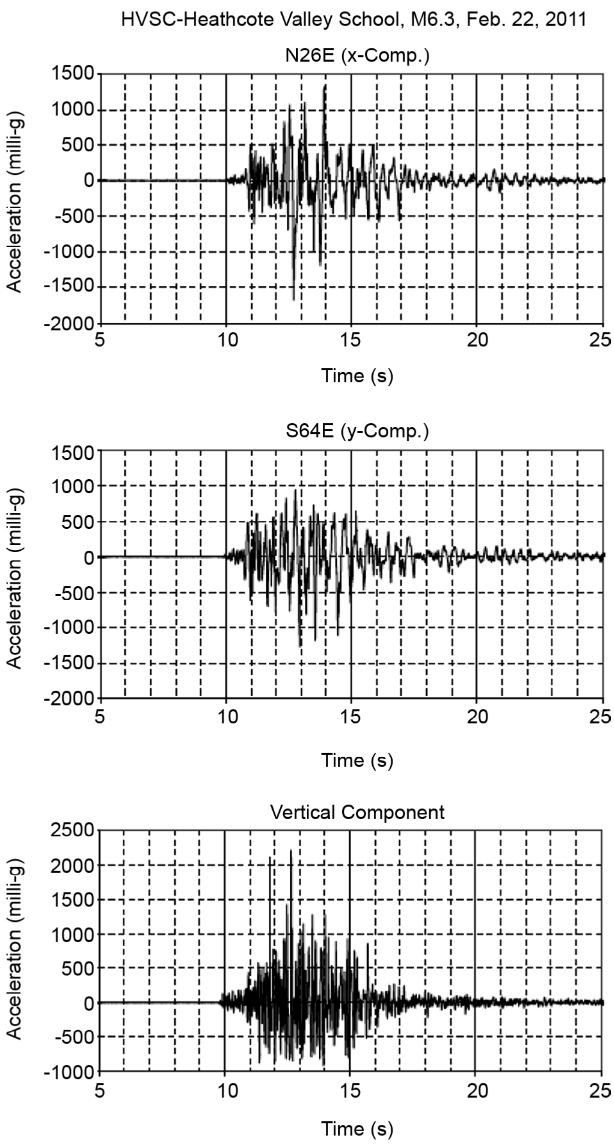

Figure 6. Heathcote valley School damage (from Berrill [2] using Geonet data).

NZ started to be designed for ductility, and from 1985 capacity design considerations were followed in design which means that in post-1985 RC seismic frame inelastic response occurred primarily in the ductile elements. From 1992, more stringent ductility detailing requirements required that gravity columns be designed to undergo lateral displacements expected in the seismic frames and that stairs would slide and not carry significant interstorey shear forces. In general, well-designed and detailed commercial buildings had no major structural damage if they were on a good foundation. Some had significant beam elongation and crack opening in the plastic hinges. While many buildings were designed to have hinges at the column bases, this seldom occurred (according to discussions with John Hare) possibly to the flexibility of the foundations. Unfortunately, some buildings were not on a good foundation, and while there was no structural damage, they had differential column settlements. Many buildings were out-of-plumb after the earthquake. Some buildings suffered partial collapse (like the PGC Building with 15 lives lost) or total collapse (like the CTV Building) with 115 lives lost. Other taller buildings satisfied their "life safety" performance goal, but lost their stairs, like the Forsyth Barr building, and many had to be replaced after the earthquake because it was difficult to perform a proper repair. It should be noted that some buildings were recognised as being vulnerable to strong ground shaking before these events. This includes not only older URM structures but some of the more modern concrete structures too.

9. Many reinforced block masonry buildings behaved very well, but those not reinforced did not behave well.
10. Steel buildings generally behaved as, or better than, expected given the level of shaking. This may be because of the high strength-to-stiffness ratio of steel. As the design of most buildings was limited by drift considerations, the high strength resulted in low overall ductility demands. Some examples of damage in steel buildings were damage to non-sliding stairs in a 1986 building, and yielding of eccentrically braced frame (EBF) shear links (as was expected), and foundation settlement causing relative displacement of the floor. In two eccentrically braced frame structures, there were fractures in one or two active links. The reasons for this were subsequently determined to be because of poor demands, substandard steel material, and high shaking demands. However, even in these cases, the damaged regions could be cut out and replaced. In fact, no significant steel buildings were demolished as a result of the very strong shaking, and steel framed buildings were some of the first to be reoccupied.
11. There was only one base isolated building in Christchurch, even though base-isolation technology was originally pioneered by New Zealanders. Liquefaction may also provide another level of isolation under the base-isolated Christchurch Women's hospital thereby protecting the structure. This hospital was able to be used immediately after the event.
12. Damage to non-structural components (ceilings, facades, parapets, chimneys, canopies) was severe in most buildings in the affected region
13. Damage of all types occurred in the continued aftershocks making repair difficult.
14. Amenities such as power, water, and sewage have taken time to restore in the liquefaction affected areas and on the hills, affecting the lives of many.
15. The total death toll from this earthquake was 185 people. Because Christchurch is a small city (400,000 people), many people know somebody who died, or know someone who was a friend of one of these people.

While significant damage occurred, it must be remembered that the shaking levels were very high. In these levels of shaking, with the current design philosophies, it could be expected that even modern structures could collapse. The fact that they did not is indeed fortunate. Reasons for the better than expected behaviour of modern structures is still not fully understood, but some of the effects may be:

i. Soft soils providing isolation and reducing the accelerations affecting the structures,
ii. Partitions and facades providing extra stiffness and strength to the structures, and
iii. Floor slabs providing more strength and stiffness than that currently considered in design.

3. Post-Earthquake Issues

3.1. Immediate 22 February Aftermath

After the earthquake, Urban Search and Rescue (USAR) from many countries assisted in searching for survivals and removal of bodies. Over 10,000 homes were uninhabitable. These were mainly in highly liquefied suburbs such as Bexley or in houses around the hills.

In December 2010, recommendation on decisions for damaged houses on liquefied soil, as well as proposals for foundations of houses on partially liquefiable soil had been proposed. These recommendations were able to be used again after the February 2011 event.

3.2. Earthquake-Prone Buildings

Earthquake-prone buildings are defined according to the 2004 Building Act as those which have an earthquake resistance of less than 33% of the current code. Every council was required to have a policy on earthquake-prone buildings which was to be updated every 5 years. Many NZ councils had passive approaches, such as requiring retrofit only when there was a change in use. Christchurch City Council required retrofit of these structures but the timeline was 30 years. After the damage seen in the September 2010 shaking, the council had proposed that retrofit to 67% of the current code should be required in a shorter timeframe. This proposal received a lot of criticism from earthquake prone building owners as they argued that the requirements were too severe. After the February 2011 shaking, not many earthquake prone buildings were left standing.

Many damaged unreinforced masonry heritage structures were pulled down. While the trade-off between history/culture and safety has been well recognised, as a result of the shaking the pendulum has swung towards safety. Also, according to Win Clark, post earthquake experience has shown that the only way historic places can be saved is if there is an owner with both the will and the funds to save a particular building.

For those that were remaining, arguments about the 67% level stopped. The earthquake damage has resulted in more strict ordinances on unreinforced masonry buildings throughout New Zealand. For example, the Ashburton District Council now requires important buildings to reach 67% code in 5 years and others to reach 33% in 15 years [5].

3.3. Future Shaking Level

After the earthquake, engineers wanted to know the appropriate level of shaking for future design, given the significant events that had occurred and the large aftershocks. Some people stated that the pre-earthquake zone factor (representative of seismic hazard) corresponding to a peak ground acceleration (PGA) of 0.22 g was still appropriate as the energy should have been released from the shaking. Others, seeing the aftershocks, thought that it should be increased to 0.55 g, which was seen in the biggest shock. There were other people with other opinions. The loadings committee met and discussed this issue as a matter of urgency. Studies of previous earthquakes, such as the M7.1 1968 Inangahua earthquake have indicated that significant aftershocks could occur for several tens of years after the main shock. Therefore, the risk of similar shaking in Christchurch as a result of the M6.3 event was considered to be 6% in 50 years, whereas before it was considered to be less than 1/10 of that. Geological and Nuclear Science (GNS) recommended that a more appropriate value for design seismic hazard should therefore be a zone factor of 0.30 (McVerry 2011, personal communication). Several other considerations were made by representatives of the NZ earthquake loading code. These include:

- The lack of major structural damage of some, but not all modern structures, whereas significant damage should have been expected under the very high levels of shaking. (It should be noted that since this decision, more thorough investigations of the behaviour of modern buildings has been undertaken and significant damage has also been found in many new buildings).
- The public sentiment that we should design for something stronger than previously,
- The desire not to penalize owners who had retrofitted their structures to 100% of the previous code level corresponding to the PGA of 0.22 g. Since the new requirements for earthquake prone structures required them to be retrofitted to 67% of the new code level, increasing the new design PGA to more than 0.22/0.67 =

0.33 g would mean that these structures would need to be subjected to more severe retrofitting.

- The desire by some to ensure that the design PGA for Christchurch did not become as high as that for Wellington with 0.40 g PGA, where there was considered to be significantly higher overall seismic risk.

It may be seen that the decision, while containing technical information was significantly tempered by political considerations. The final design recommendation was that the new standard design PGA for Christchurch and environs should be 0.30 g for structures with fundamental periods of up to 1.5 s. For structures with periods greater than this period, a special study was recommended. This was because of the hump in the spectral acceleration curve at a period of about 3.0s as shown in Figure (5).

At the meeting, where this value of 0.30g was first proposed to engineers in Christchurch, there was surprisingly little debate. This may possibly because there was relief at having a decision made that meant they could move forward.

3.4. University of Canterbury Decisions

The University of Canterbury made the decision to carry out a 5 step process before allowing people to reoccupy buildings. This process was one of the most rigorous in the city. It involved the following steps.

1. Rapid Damage Assessment
2. - Structural System Evaluation for Damage
   - Structural System Risk Evaluation
3. Life Safety Systems Evaluation
4. Remediation (i.e. Hazard Removal)
5. Building WOF

These steps are discussed below. Step 1 involved a walk-through to understand obvious damage, which related to the safety of other groups entering the building. Red orange and green tagging of buildings resulted. Step 2A involved engineers looking at building plans, and determining where any damage, if it had occurred may be. Then, inspections were carried out in these areas by removing wallboard, carpet etc. After this step, it was considered that all damage would have been identified. The tagging was updated. Perhaps the most unique step carried out was Step 2B. This involved looking at plans to identify elements which were likely to be brittle and which could result in collapse if severe shaking such as that which occurred in the central city occurred at the university. (During the February event, because of the high attenuation of ground motion, the shaking at the university, which was only 3-4 kilometres from the central city had approximately one half of the intensity). Those buildings with suspect details were identified and entry was limited to removal of major objects only. It should be noted that many of these buildings had no evidence of structural damage, yet regular entry was prohibited. Step 3 involved inspection of other building systems - electrical, computer, HVAC, water, wastewater etc. Step 4 involved remediation of the buildings to remove the hazards of concern. Small wallboard cracks were not considered to be significant enough to consider. The final step involved assessment of the process by an independent consulting company. It was then signed off to provide a “warrant of fitness” for use. This process resulted in an overall reduction of risk as those buildings for which a warrant of fitness had not been obtained, were not occupied until the risk was mitigated. For a number of buildings, such as the Siemon Building (Chemical Engineering) and the Mushroom (the well known circular building with a copper roof associated with the engineering school) were considered to be too expensive to remediate and have been demolished. While the 5-step process was being carried out, and buildings were vacated, teaching occurred in various places including in tents, nearby churches, and people's houses. (Inspections were also done on these buildings to ensure they were safe). Later, as buildings were demolished, single storey prefabricated buildings were placed in a “village” on what used to be university sports grounds. Many other institutions did not follow the path of the University of Canterbury which involved considerable expense. The attitude of the president (vice chancellor) of the university was that he did not want a repeat of the CTV building disaster. This building in the city was inspected and green tagged after the September 2010 event, and the 26 December aftershock, collapsed and killed 115 people in the February 2011 event. The president of the University of Canterbury said that keeping his staff and students safe was his priority, and the CTV issues would not happen under his watch.

Students attending the University of Canterbury are from around the world. As a result of the earthquakes, the students entering to the university at the beginning of 2012 have decreased in number. The number of enrolments is particularly low in the colleges of arts and commerce as these have less unique features than other colleges. The number of engineering applicants is still high especially in civil engineering, perhaps as a result of the earthquakes, so more students are being accepted into an already full engineering program in order to increase student numbers and assist the university with its funding situation. Needless to say, after the expenses incurred as a result of the earthquakes, and with the closure of buildings and related costs, the financial situation of the university is not as good as it was.

3.5. Government Decisions:

The government consisted of the councils - Christchurch City Council, Selwyn and Waimakariri District councils, Canterbury Regional Council as well as the central government who designated a minister for the earthquake recovery, Mr Brownlee. As the councils did not have the resources, and the government wanted to manage the recovery funding, it set up CERA (Canterbury Earthquake Recovery Authority). Also, as a result of people agony after losing relatives, a Royal Commission on Canterbury Earthquakes was established. The mandate for this commission was to determine the causes of the damage and lives lost in the earthquakes. It was hoped that this would help to bring closure to those who had lost lives; it would allow lessons to be learnt so that the same errors would not be repeated elsewhere. In addition, the NZ government Earthquake Commission (NZ EQC) which provides insurance for residential properties was involved.

The Royal Commission report on the CTV building describes three "critical" factors in the collapse. These are:

- The intense horizontal ground shaking;
- Brittle columns;
- The asymmetrical layout of structural walls, causing the building to twist in the quake and place extra strain on the columns.

Moreover, concrete in the columns was significantly weaker than expected. It also describes a breakdown of systems at many levels which allowed a structure of this type to be designed [6].

Much of the central business district (CBD) was red-zoned. This meant that no entry was permitted into large areas of the city as it was under military lockdown. Looting was avoided; however, the closure that affected the shops and offices of more than 50,000 people has had a major economic effect on the city. Many businesses moved to the western suburbs. This red zone has been shrinking as buildings are removed and the safety is improved. A year after the event, the city is still being opened to public in stages. Some buildings which are adjacent to severely damaged tall buildings (like the Grand Chancellor Hotel) have been out-of-bounds until these buildings were stabilized or deconstructed to mitigate the adjacent building hazard.

There are issues about whether buildings will be rebuilt on some liquefaction areas and near steep hill areas. While it is possible to build almost anywhere, some areas will not be rebuilt. In 2012 the government decided that the suburb of Bexley was one of these areas [7]. This area used to be a rubbish dump. However, developers convinced the council that it was appropriate to build there, and many new houses were constructed on this area. The silt coming up inside the houses as a result of this liquefaction during every aftershock is not clean. Parts of Avonside have also become parks. In February 2012, after the engineers had completed checks and calculations, Merivale Mall was immediately closed as a result of the military powers of CERA [8] the Canterbury Earthquake Recovery Agency.

The government has also been making efforts to implement building ratings which will be displayed to the public. There has been significant support for this in concept and it is believed by many that such a rating system will be more effective than specific legislation to remove poor buildings from the city landscape. The SEAONC 5 star system is being used for ideas as part of this. There has been discussion that such a system could be problematic if it is based simply on building age, and while it could be based on calculations, very few engineers have the tools or experience to estimate the likely collapse of a building, especially if the complete building plans, including major structural upgrades, are not available as is the case with many buildings. This proposal is still in progress at the time of writing.

3.6. Engineering Activities/Decisions:

Immediately after the September 2010 event, a clearinghouse was established. Here, researchers from around the world met almost every night to exchange information, obtain permission to visit certain areas, and to plan further activities. This clearinghouse was initially established by academic staff at the University of Canterbury. GNS Science and the NZSEE also shared leadership of it at different stages. The NZSEE established a position for one person to become the liaison person for the many international guests who came from overseas.

Volunteering engineers performed rapid damage assessments (both Level 1-exterior and Level 2-interior) of all buildings in the days, weeks and months after the earthquake. Later on, they received payment for this work. They also assisted the city council to develop an inventory of building types. Training for the tagging occurred every morning. However, even with the training, there were significant discrepancies in the quality of tagging conducted. Some buildings which had not been damaged were red-tagged (i.e. entry was prohibited) as a result of them being in the shadow of another building that had been damaged. For example, the 26 Storey Hotel Grand Chancellor suffered the loss of one storey on one corner. About one year after the February event, demolition was initiated. The demolition was conducted slowly, piece by piece, starting at the top, because a more rapid destruction, such as that using detonation, would cause damage to surrounding buildings and initiate lawsuits.

For buildings that had been damaged and for which re-entry was permitted, the occupants/owners often asked how much the earthquake resistance has been compromised as a result of the ground shaking. In order to answer this question, a lot of information is required. This may include the initial capacity of the structure in terms of earthquake resistance, the demands on each individual element during the various aftershocks, and the degradation of the response due to the various aftershock demands. Alternatively, it may be possible to estimate the capacity of the damaged structure from observations of its damaged state. Whichever way the remaining "earthquake life" is estimated, any estimate will be very approximate as it is difficult to estimate the collapse life of a newer structure. For example, understanding low cycle fatigue effects of structures is still in its infancy. Also, no building had comprehensive instrumentation, so it is difficult to estimate demands. Nevertheless, a decision needs to be made after any building has experienced strong earthquake shaking as to whether it should be:

a) Left as is and reoccupancy permitted;
b) Repaired before reoccupancy. In this case decisions must be made about the level of repair required to provide a specified level of remaining earthquake resistance, and the cost of the repair method is also considered;
c) Demolished.

Substantial efforts have gone into documents to assist engineers, who generally have no experience in making these decisions, with appropriate guidelines.

Because modern buildings generally behaved better than expected given the level of shaking and the design philosophy, there have been discussions about the appropriateness of the current design procedure to meet a specific performance objective. Some people have indicated that because modern structures behaved (in general) significantly better than considered in design, that the design accelerations may be significantly reduced to provide the specified level of performance. It should be noted that the NZ public would not have accepted lower design levels immediately after the earthquake. It is considered that soft-soil effects, slab effects and non-structural effects, which were not considered explicitly in design, may have contributed to the increased performance. These effects are not present in structures on stiff soil which have either no non-structural elements or slabs, or non-structural elements or slabs considered realistically in the design process. For this reason, for code specifications required to provide safety of the range of building structures (including those in which there are no slabs and those with no non- structural elements, like some parking structures) on all soil types, reductions of the earthquake design demand are inappropriate. It also follows that buildings containing significant non-structural elements and slab effects likely to affect the structural response, but that are not considered explicitly in design have the possibility of different behaviour than that anticipated. It is possible that the behaviour could be (i) worse due to a change of mechanism, or (ii) better as was observed from many buildings in Christchurch. For the reasons described above, additional parameters to design structures for lower capacities are not likely to be approved.

A Royal Commission on the Canterbury earthquakes was established to understand why certain buildings collapsed, and to ensure that lessons were learnt to ensure that further undesirable behaviour of the sort observed could be avoided in the future. While the role of the commission was not to apportion blame, the process of understanding why people were killed allowed and negligence to be seen by the NZ public, and the police are considering legal action against a number of individuals in this respect. Many technical and non-technical reports and presentations are freely available for download from the Royal Commission website.

There has been a lot of talk about the use of low-damage structures in the Christchurch rebuild. These include base-isolation (which seems to be popular), discussions of rocking systems, post-tensioned beam systems, and other systems [9]. Research investigations were underway at the University of Canterbury even before the earthquakes, funded by the Ministry of Science and Technology Natural Hazard Platform, industry groups promoting concrete, steel and timber buildings, fabricators and others. The Structural Engineering Society (SESOC) has recommended against using post-tensioned beam structures for a number of reasons, including the pushing apart of the columns, and the likely damage to the floor slab as described in Buchanan et al [10].

A lot of care was taken to ensure that people go back into the CBD safely. Even at the time of writing this paper, about 2 years after the 2011 earthquake, there is still a RED zone into which ordinary people are not permitted. Use of the red zone has been commended and criticized. On one hand, people are safe and property is not stolen, while on the other side, people are not allowed to work in their business/offices in the downtown and many are moving away to other centres and starting a new life. Every extra day the city is closed, the number of displaced people returning back to Christchurch reduces.

3.7. Insurance Decisions

The city of Christchurch is very well insured. Any home that has a mortgage has earthquake insurance. Part of the insurance payment goes to the government run earthquake commission (EQC). The earthquake commission pays out the first $100,000 of insurance on each house. After this amount, private insurance is used. Commercial buildings are generally insured at a low rate directly with insurers (and their reinsurers). Even when one of the local insurance companies, AMI, with many of its clients in the Christchurch area, did not have sufficient reinsurance and had financial difficulties after two earthquakes, the government agreed to assist this company.

After the M6.3 earthquake, insurance companies stopped providing insurance on structures in the region. This even includes non-earthquake insurance. Without insurance, banks would not lend. Without money to borrow, most people could not buy. Insurance is still slow in becoming available even 12 months after the event. Insurance companies have stated “how can we insure a house that is on fire”, as an analogy to Christchurch houses still subject to aftershocks. This is having a significant economic effect on the economic recovery of the whole region.

Over $15 billion of insurance funds will flow into the region over the next few years. This will revive the business opportunities in Christchurch.

EQC chief executive, Ian Simpson, stated that risk models probably did not pick up well “second-order effects” from aftershocks, and that there needs to be a better view of the land damage and the effect of land movement on building damage. The Christchurch earthquake sequence has not changed the commission's view of Wellington or its worse-case scenario. The Probable Maximum Loss for Wellington is expected to involve 150,000 claims for a major earthquake there. In Christchurch, there have already been more than 430,000 claims. The way EQC operates is being evaluated to see if there are better ways to allow homeowners to manage their risk considering the social risk management trade-offs that are involved in any system.

Because of the long time taken for repairs to be made to many houses, the EQC is allowing some homeowners to take the insurance money rather than wait for all the repairs. One consequence of this is the possibility that some homes will not be repaired following an event.

Also, because insurance companies want to avoid payments on frivolous claims, and because large payments are not good for their business, it has been reported that insurance advisors who worked in Hurricane Katrina have been advising insurers in NZ regarding ways of delaying or avoiding payments. This is creating a bad perception of the NZ insurance industry.

3.8. People's Decisions

By June 2012, approximately 3% of the population had left Christchurch as a result of many reasons including loss of business place, loss of business opportunity, damage to homes, emotional distress from more than 3200 felt quakes (measuring magnitude 2.8 or above) since September 2010.

4. Summary of Lessons

- Significant shaking around Christchurch occurred on previously unknown faults. This is also true for other recent significant earthquakes around the world. The importance of considering this pos-sibility explicitly in earthquake design codes is therefore reemphasized.
- Waves released from ground rupture have directionality and local site effects which can result in significantly greater shaking than that considered as a possibility (i.e. the maximum considered event, MCE) for a specific region. It is important that building owners and the public are aware of the level of shaking that a city is being designed for, the philosophical approach used for buildings subject to this shaking, and the fact that this may be significantly exceeded.
- Ground deformation effects, including liquefaction, rockfall, and lateral movement on hillsides and in liquefaction prone areas, may have a significant effect on both damage and economic loss in a region.
- The possibility of significant aftershocks should be included explicitly in earthquake loss and insurance programmes.
- The "life safety" performance objective for building structures under the design level of earthquake shaking was achieved in shaking much greater than the design level shaking. This indicates that many structures had extra factors of safety due to foundation conditions, the effect of slabs, and non-structural elements, which limited the demand.
- Engineers are efficient at designing new structures or making additions/alterations to existing structures. However, they generally have little or no experience of damaged structure performance assessment. Furthermore, while FEMA306 and other documents exist, they were often inappropriate or incomprehensible for the NZ situation, there is little good guidance or help with the decision that must be made for a damaged structure regarding it should be:
  a) left as is,
  b) demolished and replaced, or
  c) repaired (and if-so, what repair method is best)
  Further guidance and training about this decision, considering likely cost and time issues, is required if engineers are to become competent in this role.
- While it is possible to protect life with buildings constructed following modern building codes, many structures may need to be replaced following the event(s). Unliveable houses and business premises that cannot be entered cause major social and economic implications for a region. This was a major issue in the Christchurch Central Business District where about one half of the major buildings required replacement. Future efforts should be to develop "low-damage" construction which can be usable after a major event.
- When people have no acceptable place to live, and/or work, there is a tendency for them to move away from the effected region.
- Insurance can be very positive bringing billions of dollars into a region. This "new income" to a region provides employment and affects house prices.
- Insurance companies do not make money by making full payments in a timely manner. They have many incentives to delay payments and to pay the minimum amount possible.
- Approval for changes or reconstruction from insurance companies may take many years.
- The issues relating to land use are the same as those for other disasters. These were expressed in The Economist [11] and are summarised below: The right role for government, then, is ... to minimise the consequences when disaster strikes. At present, too large a slice of disaster budgets goes on rescue and repair after a tragedy, and not enough on beefing up defences beforehand. Second, government should be fiercer when private individuals and firms, left to pursue their own self-interest, put all of society at risk. Third, governments must eliminate the perverse incentives their own policies produce.
  When governments rebuild homes repeatedly struck by disasters, they are subsidising people to live in hazardous places.
- Much has been learnt about earthquake engineering over the past decades. It is a credit to our

fathers and grandfathers that they developed techniques to prevent building collapse thus protecting people's lives in a significant earthquake. They ensured a political process that considers this technical knowledge in legal requirements for design and construction throughout New Zealand. It has been estimated that, without these efforts, rather than 185 people dying, there would have been around 3000 deaths and many injuries. Gratitude is therefore grateful due to our fathers and grandfathers for their insight, wisdom and determination in establishing these systems.

At the same time, the lack of insight and wisdom of our fathers and grandfathers has caused significant frustration. While they had performed work and political processes to protect life, they did not aim to protect the infrastructure in very strong shaking. Therefore, while most structures remained standing, many had to be demolished. This has resulted in major economic loss and inconvenience to the region.

There is therefore a challenge to this generation to develop systems that will protect our infrastructure. This involves a paradigm shift from "damage-prone" design and construction, to provide construction which will sustain little or no damage during a major event. It involves new technical developments and political changes. Resulting legal requirements must be applied not only specific buildings, but all buildings in a city/community, as their resilience/ performance/ sustainability may be affected by the resilience/ performance/sustainability of the weakest structural system in the community. This challenge, for the sake of our children and grandchildren, is to not only save lives, but also to economically protect our infrastructure so that our children and grandchildren look back with gratitude on our efforts.

5. Conclusions

This paper described the ground shaking and the damage experienced in the February 2011 Christchurch earthquake. Also, there were a number of lessons from the 2011 Christchurch earthquake related to the level of shaking, effects of aftershocks, the effects of ground movement (liquefaction, sliding or rockfall), structural damage, and insurance. These are all related to political issues which control how earthquake events are managed.

References

1. MacRae, G.A. (2011). The 2010 Canterbury Earthquake, *Sixth International Conference of Seismology and Earthquake Engineering*, Tehran, Iran.

2. Berrill, J. (2011). Some Aspects of the M6.3 February 22nd Earthquake, Unpublished Document, Civil Engineering, University of Canterbury. Referenced in Friday News.

3. Somerville, P.G. (2003). Magnitude Scaling of the Near Fault Rupture Directivity Pulse, *Physics of the Earth and Planetary Interiors*, **137**, 201-212.

4. Cousins, J. (2011). GNS Science, Email Correspondence following the Feb. 2011 Earthquake.

5. The Press (2012b). http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/6401797/Outlying-districts-get-tough-on-quake-rules.

6. The Press (2012a). http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/6395045/CTV-building-report-very-thorough.

7. The Press (2012c). http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/6397075/Hundreds-newly-red-zoned-but-many-in-limbo

8. The Press (2012d). http://www.stuff.co.nz/the-press/news/6403205/CERA-report-prompts-mall-evacuation

9. MacRae, G.A., Clifton, G.C., Mackinven, H., Mago, N., Butterworth, J., and Pampanin S. (2010). The Sliding Hinge Joint Moment Connection, New Zealand Society for Earthquake Engineering.

10. Buchanan, A.H., Bull, D., Dhakal, R.P., MacRae, G.A., Palermo, P., and Pampanin, S. (2011). Base Isolation and Damage-Resistant Technologies for Improved Seismic Performance of Buildings, Report to the Royal Commission for the Canterbury Earthquakes, New Zealand, http://canterbury.royalcommission.govt.nz/.

11. The Economist (2012). The Rising Cost of Catastrophies.