2011 Christchurch Earthquake: Event's Lifecycle Response and Critical Lifeline Systems Recovery

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On September 4th 2010 at 4.35am (NZ standard time), a M_w7.1 Earthquake occurred when the previously unknown Greendale fault ruptured on the Canterbury plains at about 30 km west of Christchurch, New Zealand. The initial rupture generated a series of aftershocks in the following months culminating with a major M_w 6.3 earthquake on February 22nd 2011 at 12.51pm. With the epicenter located only 10 km south-east of Christchurch city center at a shallow depth of 5 km, the event has claimed the lives of 181 people, generated major damage to infrastructures and became the worst disaster in the history of New Zealand in terms of economic losses (Napier earthquake in 1931 still remains the most deadly event with 256 causalities). This paper briefly presents a summary of the seismic events that have affected the Canterbury region in the South Island of New Zealand since September 2010 until the catastrophic event in February 2011. It also describes the response protocols implemented by both public and private organizations to manage and restore the numerous lifeline systems affected so better practices can be adopted in the future.

Key Words : *Earthquake Response and Recovery, Critical Infrastructure, Lifeline Systems.*

1. INTRODUCTION

The country of New Zealand (NZ) is located in the south-western Pacific Ocean and comprises two large islands (the north and the south islands). Its population is about 4.2 million people and the Gross Domestic Product (at a purchasing power parity[1]) estimated in 2010 was $117.8 billion (1).

New Zealand is notable for its geographic isolation. Australia on the west and New Caledonia, Fiji and Tonga on the north are its closest neighbors. The three most populated regions are Auckland,

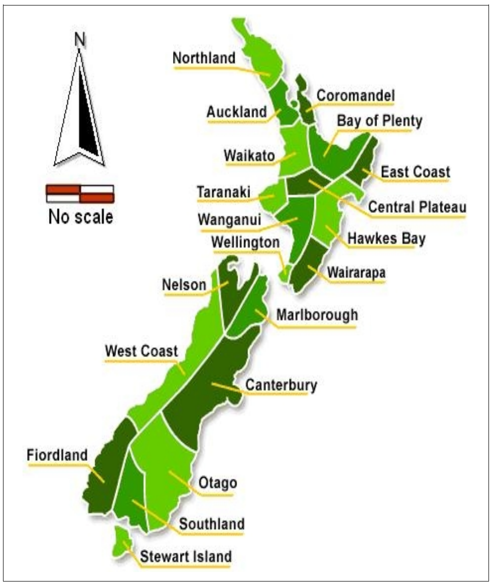

Figure 1 New Zealand Regions.

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[1] GDP at purchasing power parity (PPP) gives the gross domestic product or value of all final goods and services produced within a nation in a given year. A nation's GDP at PPP exchange rates is the sum value of all goods and services produced in the country valued at prices prevailing in the United States.

Wellington and Canterbury (see Figure 1) with 1.3 million, 450 thousands and 520 thousands people, respectively (2). These areas comprise more than 50% of the total population and are the prominent businesses centers responsible for most of the trading, services, export, import and industry activities nation wise.

Over the last 20 years, the country has been transformed from an agrarian economy to an industrialized market economy that can compete globally (1). However, its importance in the worldwide industrialized marked is considerably small when compared to big economies such as Australia (its most significant trading partner), United Kingdom, Germany, France, China and United States. In this context, New Zealand still shows traces of an agrarian economy with most of its its exports profile based on agricultural products (e.g. dairy products, meat, wood, wooden products and fish).

The small scale economy combined with the numerous natural hazards experienced in New Zealand make disaster management a challenging field. The country is situated on the boundary of the Australian and Pacific plates and just above the 'roaring forties' (strong westerly winds found in the Southern Hemisphere at 40-49º latitude). Hence, it is vulnerable to land slides, climate events (intensive rain fall, flooding and snow storm) and seismic activities (earthquake tremor and volcanic eruption). Additional hazards experienced in NZ are hail precipitation, electric storms, extreme hot or cold temperature exposure, strong winds and tornadoes; however, their impacts range from low to nought (3).

The multi-hazard environment led both government and private sectors to develop and implement a number of mitigation strategies to reduce risks associated with disasters as well as better prepare to respond and recover from events. For instance, it can be cited the recently revised Civil Defence and Emergency Management Act 2002 (4), strict building codes enforced by the Institute of Professional Engineers New Zealand (IPENZ) and the strong financial scheme implemented by the Earthquake Commission (EQC) established in 1945. The former ensures insurance payment provisions in case of disasters, such as earthquake, natural landslip, volcanic eruption, hydrothermal activity, tsunami (5).

This paper has been divided into 4 sections. After this introduction, the NZ tectonic setting and the series of earthquakes experienced in Canterbury and Christchurch are described. The third section presents the response implemented after the deadly earthquake on February 22nd in Christchurch. The paper is concluded with initial findings in regards to response and recovery operations.

2. NEW ZEALAND TECTONIC SETTING AND THE CANTERBURY EARTHQUAKE

About 140,000 earthquakes are recorded in and around New Zealand every year (3). Such highly seismic activity is associated with the two tectonic plates located underneath the country. According to Norris (6), "on the northeast and underneath the north island the pacific plate is been subducted below the Australian Plate and on the south of New Zealand and underneath Fiordland both plates are moving towards each other, but in this case the Australian Plate is being subducted under the Pacific Plate" (see Figure 2). The country is located where the plate boundary changes from a subduction zone running down the East Coast of the North Island which terminates off the Northeast coast of the South Island (about 100 km north of Christchurch) to a transform boundary cutting through the continental crust of the South Island. Overall, all of the relative motions between the Australian and Pacific plates are not accommodated on one or two faults in a narrow zone, but on many faults across a much wider zone where large near-plate-boundary faults accommodate this complex distributed deformation.

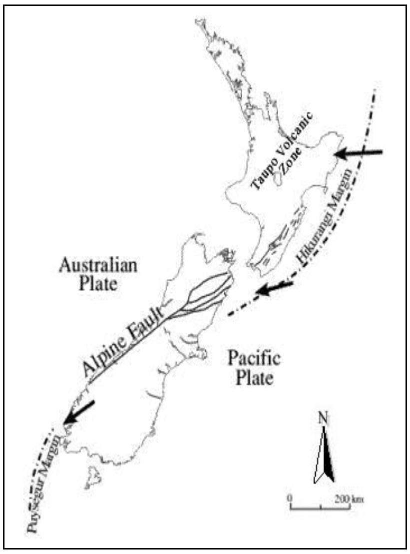

Figure 2 New Zealand Tectonic Setting (6).

Several destructive earthquakes have driven a strong research and policy making focus on risk mitigation and emergency response. The most studied areas are the bottom part of the North Island (Wellington) and the Alpine Fault in the South Island. These areas are focused due to the high population density in the capital (Wellington), the physical extend of the Alpine Fault and possible catastrophic series of events (e.g. liquefaction, ground displacement) associated major ruptures.

A series of seismic events starting on September

4th 2010 culminated with a major aftershock on February 22nd 2011. The event was the most destructive earthquake since Napier Earthquake in 1931 and quickly became a catastrophe for Christchurch city as well as an opportunity to implement and assess long developed earthquake engineering practices and response procedures. The next sub-section discusses the seismic events unfolded after the initial M_w 7.1 earthquake on September 4th 2010.

(2.1) 4 September 2010 Darfield (Canterbury) earthquake

At 4:35 am (NZ Standard Time) on September 4th the rupture of the previously unrecognized Greendale strike-slip fault beneath the Canterbury Plains of New Zealand's South Island produced a M_w 7.1 earthquake that caused widespread damage throughout the region. The event produced a ≥ 28 km long, dextral strikeslip surface rupture trace, aligned approximately west-east, with a component of reverse faulting at depth (7). A maximum horizontal displacement of approximately 4.5m and up to 1m of vertical displacements occurred at the surface rupture. The surface rupture trace occurred in an area of high intensity arable and pastoral farming leading to significant land damage in the rupture zone. Close to the fault the strong ground shaking resulted in felt intensities as much as MM9 (New Zealand Modified Mercalli Intensity) and peak ground accelerations over 1.2 g near to the fault. However, a maximum PGA of approximately 0.3 g was experienced in the city of Christchurch 30 km away. During this event, extensive liquefaction, differential subsidence, and ground cracking associated with lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Taitapu towns.

The Greendale Fault was not previously recognized as an active fault because there was no evidence for its presence beneath the Canterbury Plains, an active fluvio-glacial fan system which was last resurfaced at end of the last glaciation (~16,000 years ago). However, it is believed that the newly-revealed Greendale fault was pre-existing, and this has been confirmed by seismic reflection surveys conducted after the September 4th event (7).

Given the E-W strike of the Greendale Fault, it is very likely that this fault first formed during crustal extension of Zealandia more than 50 to 60 million years ago. E-W trending faults are present throughout Canterbury and offshore on the Chatham Rise, and some of these are now "active" faults, i.e. faults that have the potential to generate earthquakes in the modern setting (J. Pettinga, pres comm. 2011).

Between September 4 to October 16 seismicity of M ≥ 3 showed an eastward expanding pattern of aftershocks, suggesting an eastern transfer of stress through the crust. Between November 2011 and January 2012 episodes of seismicity on previously unrecognized "blind" NE-SW trending faults were apparent. Two were located at each end of the Greendale fault and one beneath the Christchurch Central Business District (CDB), which caused further damage on 26 December 2010. Then between January 15 and February 21 small episodes of seismicity occurred in an aftershock zone to the east of the Greendale fault in the Rolleston, Lincoln, Halswell areas. Earthquakes were less frequent and in accordance with Omori's Law (8).

(2.2) 22 February 2011 Christchurch earthquake

Following the developments from the Greendale Earthquake, on February 22, a M 6.3 occurred 10 south east the center of Christchurch city at a shallow depth of 5 km during the middle of a working day. The shake resulted in widespread destruction, injuries and deaths in Christchurch. The event is believed to have produced a rupture of an 8 x 8 km fault running east-northeast at a depth of 1–2 km depth beneath the southern edge of the Avon-Heathcote Estuary and dipping southwards at an angle of about 65 degrees from the horizontal beneath the Port Hills. Fault motion was dominantly dextral strike-slip, but with a large reserve thrust component. There appears to have been no surface rupture, however satellite images indicate the net displacement of the land south of the fault was 50 cm westwards and upwards. It is a shallow fault with high fault friction and co-seismic stress drop, which produced highly directional seismic energy towards Christchurch city. The interbedded layers of gravels and sands under Christchurch created a "slap down" amplification of seismic waves, increasing ground acceleration and thus damage (8 and 9).

Vertical accelerations in Christchurch were far greater than the horizontal acceleration, with the PGA in central Christchurch exceeding 1.8 g and the highest recording of 2.2 g at Heathcote Valley Primary School, resulting in shaking intensities of MM10+ in the New Zealand Modified Mercalli Intensity. This is one of the largest PGA's ever recorded and considered extremely high for a M_w 6.3 earthquake. Such accelerations significantly exceeded building design codes enforced in the country based on previous seismic activities (9).

It is probable that the M_w 6.3 Christchurch earthquake was triggered by a change in the regional stress field due to the M_w 7.1 Greendale earthquake. However, there was no previous evidence of faulting, or significant aftershock activity which may have suggested significant further eastward continuation of seismicity after the 4 September Darfield earthquake.

In summary, the events between September 4th 2010 and February 22nd 2011 are as follows:

- 2256 ML ≥ 3 (locally felt)
- 281 ML ≥ 4 (felt across larger areas, locally scary)
- 28 ML ≥ 5 (regionally felt, locally very scary and partially damaging)
- 3ML ≥ 6 (regionally scary and catastrophically damaging)
- 1 ML ≥ 7 (felt across NZ South Island, regionally damaging)

This earthquake sequence conforms with other near-plate-boundary long-recurrence-interval-strong-fault situations (such as the 1993 Landers M_w 7.2 earthquake in California). These events are typically characterized by strong faults with slow slip rates, long recurrence intervals, high stress drops, temporal clustering of large earthquakes and prolonged aftershock sequences (8).

3. EMERGENCY RESPONSE AND LIFELINE RECOVERY

In the light of the seismic events described in the last section, an analysis of the response actions and lifeline recovery is presented as follows. To do so, data collected from media reports and field research were used as well as two time-frames defined for proper analyzes: response and recovery.

(3.1) 2011 Christchurch Earthquake Response

The unexpected event on February 22nd 2011 has badly impacted a number of critical systems. Although the tremor generated very high Peak Ground Acceleration (PGA) and the shake intensity was more than twice the required in the building codes in New Zealand (10), the overall performance of structures was decisive in protecting life. Moreover, well prepared organizations and repeatedly trained procedures supported an efficient response to the event. Findings of good response practices in the light of organizational arrangements are possible to be drawn by reviewing the impacts on lifelines and immediate reaction as follows:

Victim Support and Welfare Centers: immediately after the event at 12:51pm, two main points were set up for those unable to safely return home or to find alternative accommodation. Two victim support centers were set up at Hagley Park near the city center and at Addington Race Course southwest of the city center. Hagley Park welfare center reached capacity as early as the first evening and people seeking shelter were diverted to Addington center. By day 4, numerous welfare locations were available to the public, including Cowles Stadium, Burnside High School, Pioneer Recreation and Sport Center, Rolleston Community Center and Rangiora Baptist Church. Overall, it was estimated that 450 people were staying overnight in the welfare centers in the first four days while residents were encouraged to go seek support at locations in the outskirts of Christchurch city to reduce pressure on already overloaded critical systems.

Water Supply: the water distribution system was badly affected by the earthquake with only approximately 40% of the city having access to water by Day 4. Additionally to very limited water supply, residents were required to boil water before drinking and cooking. In order to increase fresh water supply, two desalination plants were set up by New Zealand Army at Lyttleton and New Brighton suburbs with capacity to produce 2,000 liters of water per hour at each site as well as distribution at numerous locations was implemented using tankers at specified times of the day.

Power: estimated that in the immediate aftermath of the event, 80% of the city did not have access to power. Automatic shutdown systems functioned as designed and there were no reports of fire due to short circuit. Within four days, approximately 80% to 75% of the city had electricity supply recovered with the full restoration of service expected to take several weeks. Challenges to fully restore the service were due to damaged underground facilities and cable lines.

Transportation (road network): 32 streets and 13 bridges were closed to the public according to the Christchurch City Council. Closures were due to extensive damage or need to assess structures in order to ensure the safety of users. A key link between Christchurch CBD and Lyttleton suburb (i.e. the Lyttleton tunnel) was immediately closed to traffic and progressively re-opened. Information of road closures and works were uploaded in a map format through a combined effort between the local and regional councils.

Sewage: extensive damage to the network and long term recovery time-frame was expected. Being a secondary priority against the recovery of the water supply system, a contingency plan included disposing human waste in holes to be dug at properties' backyards and distributing chemical toilets in the worst affected areas. By day 4, more than 600 chemical toilets were delivered to Christchurch as well as extra shipments were due to arrival in the day to follow. As much as possible, the crippled network was used to dispose raw sewage into rivers as an alternative for the lack of chemical toilets and non functional house toilets.

Building Assessment: in the initial three days, building assessments activities were restricted to the badly affected area of Christchurch CBD. Focus was given to this are due to the concentration of high rise buildings in the are and lack of human resources to conduct activities. On day 4, a nation wide coordination task gathered building consent officers, Earthquake Commission (EQC) members, professional engineers and specialists from all over New Zealand, which allowed for a colossal assessment operation to take place. The assessment activity was divided into three force tasks:

- Operation CBD: continuing building assessment at the badly affected central city;
- Operation Suburb: 45 teams for house assessment in New Brighton, Darllington, Avonside, Parklands, Queenspark, St Martins, Opawa and Lyttelton. 100 teams for street and house assessment in Sumner, Redcliffs, Woolston, Ferrymead, Hon Han, Richmond, St Albans, Fendalton and Merivale suburbs; and
- Operation Shops: assessment of malls and shops in order to support restoration of basic product distribution.

Fuel: limited availability for three days following the event due to lack of power to pump it from reservoirs. By day 4, suppliers ensured supply and urged the public to do not "panic buy" as stocks were high and the city has been supplied from external regions as the major highways links were not damaged.

Food Supply Chain: the logistics systems for food distribution were not severely impacted as main road links to access the city were available. However, supermarkets were closed for structural assessment and basic products (e.g. milk and bread) were limited sold by customer until the business as usual supply chain could be restored. Appropriate response actions were observed as the three major food retailers coordinated response and liaised with external suppliers and public.

Household Garbage Collection: emphasis was given to collection of perishable food and general household garbage as lack of power incurred in the expiration of great amount of food. Recyclables were not prioritized as they could be stored for future collection without any hazard. By February 26th, the Christchurch City Council estimated that the full service restoration of service would be achieved by March 7th 2011.

*State Highway Network:*under the management of the New Zealand Transport Agency (NZTA), the major regional links to Christchurch city were not physically damaged with only a single off-ramp north of the city closed for small repairs. The NZTA cooperated with the city council to reduce public travel to minimum levels in order to facilitate response activities.

*Airport Infrastructure:*closed in the first day to allow runaway and passenger terminal building assessments. The facility was highly used to support voluntary evacuation and relief operations. The national carrier (Air New Zealand) increased its operation by adding large aircrafts into its fleet (e.g. Boiengs 777 and 747 Jumbo Jets) and offering special NZD 50.00 airfares for flights leaving from and arriving to Christchurch for its domestic network. The official airport authority estimated that over 10,000 people used the airport to leave the city by day 4, which contributed positively to the reduce the stress on lifeline systems.

Lyttleton Port: berths and port infrastructure were assessed by New Zealand Navy as early as the first day. The main aim was to ensure sea deep and assess machinery to unload cargo for relief operations. Although closely located to the Earthquake epicenter, facilities were not badly affected allowing for special services such as the arrival of a ship with emergency supplies on February 27th 2011.

Public Health System: General Practice Clinics (GPs) were reduced to 40% of total capacity and the Christchurch Hospital's top floors were partially evacuated due to burst pipes and water leakage in the initial two days. Regional and main national hospitals were operating on code red as far as Wellington and Auckland. A consistent improvement was observed on Day 3 with up to 70% of GPs open to business and main hospitals being able to meet the increased demand.

Land Assessment: launched by the EQC, this operation aimed at identifying the extend and characteristics of liquefaction in the city. It quickly became a major effort as the phenomena was responsible for structural damage due to differential settlement of buildings.

*Silt removal: r*esidents were asked to remove silt (liquefied material) to kerbside and not on grassed area and footpaths for latter collection. Volunteering support was observed throughout the city as silt removal was due to be a very laborious operation with approximately 200 k tons of material needed to be removed.

Telecommunication: both landlines and cell phone networks were overloaded immediately after the earthquake. Authorities and operators urged citizens to reduce usage after reports of trapped people in collapsed buildings were using text messages and calling to ask for help. One operator has managed to restore its network by day 4, while another operator struggled to recover its towers which have been badly affected.

(3.2) 2011 Christchurch Earthquake Recovery

The continuing series of aftershocks have challenged the recovery phase as many times work done in some parts of the city needed to be re-done. The most common example was the removal of liquefied material, which is laborious and demanding in terms of physical resources as well (e.g. trucks).

In order to cope with limited human and physical resources, recovery authorities aimed a very well coordinated recovery plan so high levels of performance could be achieved. Such decision has shown to be extremely wise in the context of New Zealand, where resources and the economy scope are limited, and the event was not extensive to a very broad area.

After the State of National Emergency was lifted nine weeks following the event, operations were formally shifted from response to recovery. To allow such transition, the Civil Defence granted full command to a newly created authority, namely Canterbury Earthquake Recovery Authority (CERA). Sharing the recovery burden was also the Christchurch City Council (CCC) so while CERA would lead the recovery strategy, policy and planning, the CCC continued to be responsible for regular council-related matters and the coordination of the Central City Plan.

In this context, recovery plans were divided into two main levels: operational and strategic. On the operational front quick infrastructure repair was targeted while on the planing side coordination was the key objective. Both are further described in more detail.

Operational: CCC responsible for water and waste issues, maintenance of street laterals, portaloos/chemical toilets, roading and traffic management, garbage kerbside collection, water conservation and restrictions (with cooperation from the regional council – ECAN) and a rodent management plan. CERA was responsible for coordination and infrastructure planning. Orion (electricity supplier) was responsible to repair the power distribution network and individual telecommunication operators had to manage their own networks.

Planning: CCC in charge of developing and ensuring a new earthquake-prone building policy, heritage protection, resource consents, CBD business putrescence cleaning; and flood protection. CERA responsible for all individual building inquiries; cordon management including access schemes for business owners to recover documentation and goods, temporary housing, demolitions and debris management, and business restoration (with support from local Councils).

4. CONCLUSIONS

All levels of governance, society and private businesses were forced to test their processes and resilience to natural hazards in the midst of the catastrophic events experienced in the Canterbury region since September 4th 2010. Continuing aftershocks and the major earthquake in the Christchurch city on February 22nd 2011 further stressed the region and its critical systems which have shown good levels of preparedness and resilience in face of the unfortunate events.

This is not to say that the response and ongoing recovery were perfect, but to highlight the continuous progress in the field of emergency management when comparisons are made with the last significant earthquake in Napier 1931. An example of good practice is the fact the well designed houses did not suffer major damage and modern buildings, although damaged beyond economic repair, were still capable to protect life (10). While some indicate excessive damage to buildings as flaws in the current codes, many in the emergency management community see the fact as an economic limitation which impairs the country to overdesign buildings due to high costs. This reasoning is proven correct when scientific evidence shows very high PGAs for a M_w 6.3 earthquake indicating that the building codes were in accordance to the NZ reality and known risks in Canterbury. Further evidence of good engineering practices is the collapse of only two buildings (CTV and PGC) in spite to the very high PGAs and the survival of many other buildings (which were expected to collapse due to the strong shake intensity) that ensured the safety of many lives.

Additionally to good engineering, emergency management practices adopted in the country were efficient as a quick response was taken by the civil defence and national authorities. The event time-line shows that 19 minutes following the quake the National Crises Center was activated in Wellington, at 2:03pm the Prime Minister addressed the nation, at 4:21pm the Christchurch Mayor declared state of emergency and less than 24hs after the event the National State of Emergency was declared. All these actions show good levels of leadership, well prepared response protocols and the effectiveness of the 2002 Civil Defence Act to support affected communities.

Finally, the unfold of the recovery efforts in Christchurch will be of great interest so success and failure factors of such strong institutional coordination scheme can be assessed to help future improvement.

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