TECHNICAL NOTE

Post-Earthquake Building Safety Inspection: Lessons from the Canterbury, New Zealand, Earthquakes

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The authors discuss some of the unique aspects and lessons of the New Zealand post-earthquake building safety inspection program that was implemented following the Canterbury earthquake sequence of 2010–2011. The post-event safety assessment program was one of the largest and longest programs undertaken in recent times anywhere in the world. The effort engaged hundreds of engineering professionals throughout the country, and also sought expertise from outside, to perform post-earthquake structural safety inspections of more than 100,000 buildings in the city of Christchurch and the surrounding suburbs. While the building safety inspection procedure implemented was analogous to the ATC 20 program in the United States, many modifications were proposed and implemented in order to assess the large number of buildings that were subjected to strong and variable shaking during a period of two years. This note discusses some of the key aspects of the post-earthquake building safety inspection program and summarizes important lessons that can improve future earthquake response. [DOI: 10.1193/1.4000151]

INTRODUCTION

The Canterbury earthquake sequence consists of a series of strong urban earthquakes that occurred in and around the city of Christchurch, New Zealand, population 348,435 (Statistics New Zealand 2006). Figure 1 shows the location of these earthquakes from 4 September 2010 until June 2012. All magnitudes reported in this paper are based on the data from GNS of New Zealand.

The earthquake sequence began with the magnitude M_w 7.1 Darfield event that occurred 40 km west of Christchurch city on 4 September 2010 (Figure 2a). Significant structural and liquefaction-induced damage occurred due to this event, although no lives were lost.

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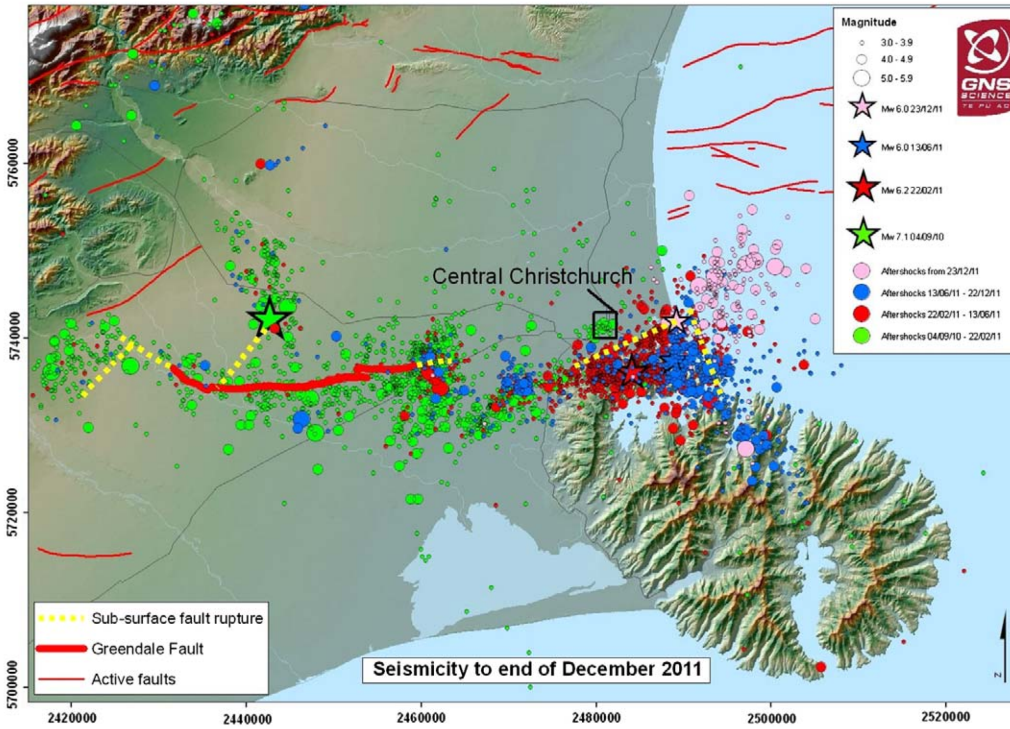
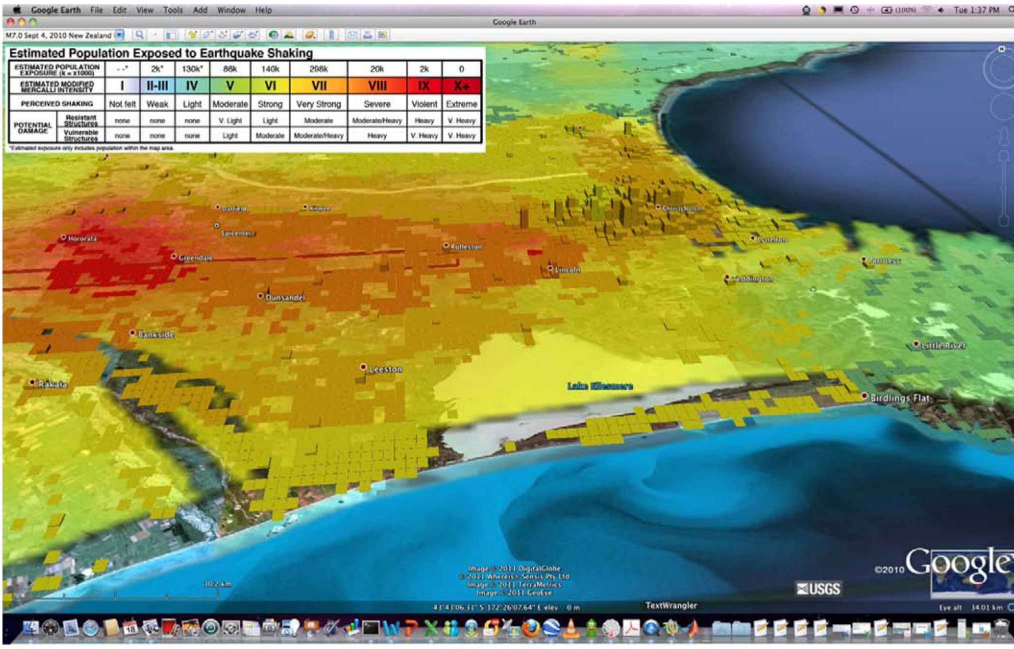


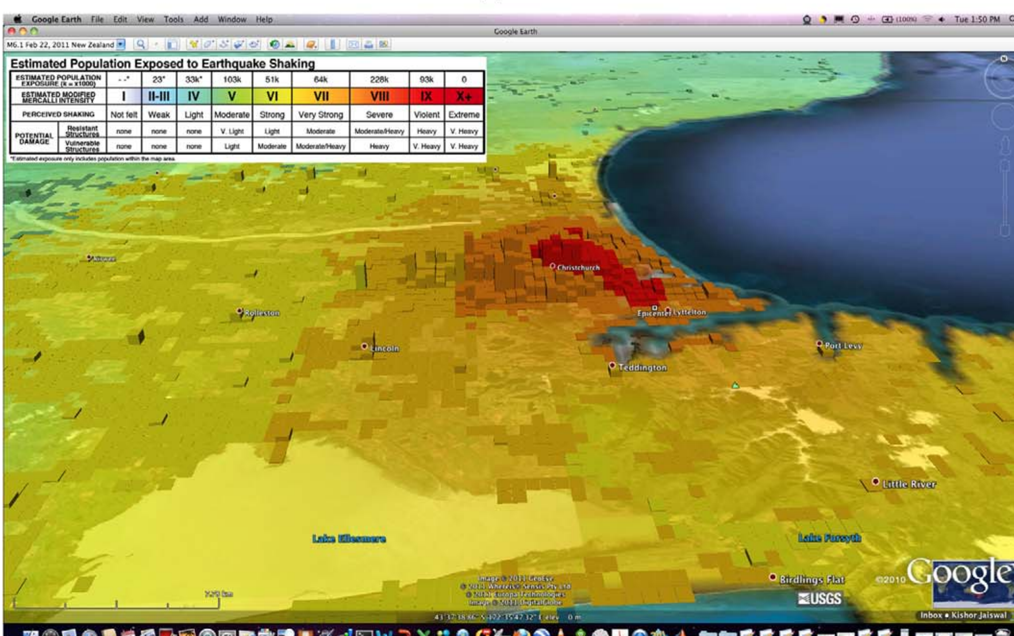
Figure 1. Map of seismic activity in Canterbury region during 2010–2012 (GNS 2012).

The second significant event, a M_w 4.7 aftershock on Boxing Day, 26 December 2010, resulted in subsequent but limited damage. Nearly two months later, on 22 February 2011, an earthquake of M_w 6.2 occurred at 12:51 pm local time (Figure 2b). The resulting shaking was widely felt throughout the Canterbury region. A larger portion of the population (over 90,000 people) was exposed to modified Mercalli intensity (MMI) IX compared to other earthquakes in the sequence (Table 1). The February earthquake caused significant damage and resulted in 185 deaths, many of which were caused by collapsed buildings in the central business district (CBD) of Christchurch city (CERC 2012). Many other aftershocks followed, including 13 June 2011, when a M_w 5.5 event occurred at 1:00 pm and was followed by a M_w 6.0 event at 2:20 pm that caused further structural and geotechnical damage. The latest significant events, as of June 2012, occurred 23 December 2011. Two earthquakes of M_w 5.8 and M_w 5.9 occurred east of Christchurch, causing significant damage. Many more details on the Canterbury sequence of earthquakes and the performance of infrastructure can be found in the special editions of the *Bulletin of the New Zealand Society for Earthquake Engineering* (NZSEE 2010, NZSEE 2011b).

The Canterbury sequence has caused unprecedented impact to New Zealand's economy with overall economic losses for rebuilding exceeding NZ $20 billion (U.S. $15.8 billion). The Earthquake Commission (EQC) has received more than 400,000 claims since the September 2010 earthquake activity. The total cost of insurance claims (insured losses) for both



(a)



(b)

Figure 2. Google Earth snapshot showing locations of stronger shaking to the west of Christchurch city. The bar height indicates the affected population at each grid cell and the color indicates the ShakeMap estimated shaking intensity (shown using ShakeMap color palette): (a) 4 September 2010 Darfield earthquake, M_w 7.1, (b) 22 February 2011 Christchurch earthquake, M_w 6.2.

Table 1. Significant events in the 2010–2011 Canterbury, New Zealand, earthquake sequence

Event	Local time	Population exposure estimated using USGS PAGER system[a]			Dead[b]	Severely injured	No. of EQC damage claims[c]	Reported direct economic loss (in USD)
		MMI VII	MMI VIII	MMI IX				
M_w 7.1 4 Sept. 2010	04.35	298k	20k	2k	0	Few	156,692	6.5 billion[d]
M_w 6.2 22 Feb. 2011	12.51	64k	228k	93k	185	164[e]	156,505	16 billion[f]
M_w 6.0 13 June 2011	14.20	236k	55k	0	0	46[g]	54,000	4.8 billion[h]
M_w 5.9 23 Dec. 2011	15.18	75k	3k	0	0	60[i]	2,200+	13–26 million[j]

[a]http://earthquake.usgs.gov/earthquakes/pager/ (accessed 19 March 2012).
[b]http://www.police.govt.nz/list-deceased (accessed 27 June 2012).
[c]Claims data accessed from http://canterbury.eqc.govt.nz/ (accessed 19 January 2012).
[d]http://www.bradenton.com/2012/03/20/3951556/iii-provides-overview-of-earthquake.html (accessed 22 March 2012).
[e]http://www.stuff.co.nz/national/christchurch-earthquake/4697308/Quake-Hope-fades-after-chapel-search (accessed 2 July 2012).
[f]http://www.bradenton.com/2012/03/20/3951556/iii-provides-overview-of-earthquake.html (accessed 22 March 2012).
[g]http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/5139172/Shattered-city-hit-again (accessed 2 July 2012).
[h]http://tvnz.co.nz/national-news/christchurch-quake-bill-could-rise-6-billion-4227216 (accessed 27 June 2012).
[i]http://www.stuff.co.nz/national/6184519/Swarm-of-quakes-hits-Christchurch (accessed 2 July 2012).
[j]http://nz.finance.yahoo.com/news/Suncorp-says-Dec-23-businessdesk-1005871691.html?x=0 (accessed 2 March 2012).

the September 2010 (U.S. $5 billion) and February 2011 (U.S. $13 billion) events is estimated at U.S. $18 billion (III 2012), making the September 2010 and February 2011 events the fifth and third costliest natural disasters in terms of insured losses, respectively, after the 2011 Tohoku, Japan and 1994 Northridge, USA, earthquakes. New Zealand national economic growth in 2011 was estimated to be 1.5% lower[k] than in 2010, and a sizable reduction in tax revenue due to the earthquake's impact is expected. The rebuilding operations are expected to continue at least until 2016 (Doherty 2011). It is still unclear how much indirect losses might be incurred due to this devastation.

In addition to the many other societal and economic issues following natural disasters, one critical need is the determination of building safety. The challenge is to quickly, efficiently, and safely inspect buildings and differentiate between buildings that can be reoccupied and those that may pose threats. The impact of the Canterbury sequence, as seen in the previous figures and tables, is singular as it has been a series of significant earthquakes

[k]http://www.parliament.nz/en-NZ/PB/Business/QOA/3/5/2/49HansQ_20110308_00000002-2-Earthquake-Christchurch-Economic-Impact.htm (accessed 10 March 2012).

requiring multiple mobilizations of a large-scale building safety assessment operation. The Canterbury earthquakes present a unique opportunity to study the safety assessment program utilized in Christchurch in order to highlight lessons learned for future events.

ATC-20 SAFETY EVALUATION PROCEDURES (USA)

ATC-20 (ATC 1989) was initially published approximately one month prior to the 1989 Loma Prieta earthquake in Northern California. It was used during the response to Loma Prieta, and improvements were made based on the experience. The next phase of work resulted in ATC-20-2 (ATC 1995), an addendum to the original document that made improvements to the procedures and updated the red, yellow, and green placards posted on buildings following assessments. In 2005, ATC updated the ATC-20-1 *Field Manual* (ATC 2005). The 2005 update to the *Field Manual* summarizes the latest methodology and includes topics and discussion not covered in the original documents. Throughout this paper, the references to ATC-20 will include the addendum ATC-20-2 and the second edition of the *Field Manual* ATC-20-1 unless noted otherwise.

The three distinct levels of post-earthquake buildings safety evaluation in the United States (and other regions of the world using ATC-20 unaltered) are Rapid Evaluation, Detailed Evaluation, and Engineering Evaluation. Licensed engineering professionals trained in safety inspection procedures typically perform building safety evaluations. Interested users are referred to the ATC-20 document, which describes the details of each evaluation procedure. After undergoing a safety evaluation, each building is posted with one of three colored placards: Inspected (green), Restricted Use (yellow), or Unsafe (red). The posting system allows owners, occupants, and the general public to understand whether the building is usable and to what extent. Rapid evaluations usually take 10–30 minutes per building and are often cursory in nature based on identifying the hazard condition associated with the building. The idea is to identify and flag any earthquake-induced hazard condition that may jeopardize safe occupancy of the structure. Hazard conditions such as structural or foundation damage, damage to floors/roof/walls, residual displacement, ground movement/settlement/slip, overhead falling hazard, neighboring building hazard, or any other hazard conditions are evaluated during such inspections. Based on the inspection, building inspectors may assign green, yellow, or red placards to the building. In addition to assigning placards, it is expected that the inspectors also recommend further actions in terms of identifying the need for barricading the area if it is thought to be unsafe. If the inspectors are unable to enter the building but find no hazards around the exterior, the Inspected placard will be marked “Exterior Only.” Rapid Evaluations are helpful in systematically identifying the condition of a large number of buildings immediately following an earthquake and in understanding the scale of the impact in terms of damage to built infrastructure.

Detailed Evaluations are typically carried out for buildings that have been assigned yellow or red placards by previous assessments. A team of two structural engineers familiar with seismic design should complete this more in-depth evaluation. It should also consist of exterior and interior inspection of the structural systems for both gravity and lateral loads. This type of inspection could take one to four hours depending on the size and geometry of the building and does not require exposing structural systems in most cases. It is likely that structural drawings would not be available during these evaluations.

Engineering Evaluations are mentioned in the ATC-20 documents, but they are not described in detail. A qualified structural engineering consultant hired by the building owner is required to analyze the structure and design the required repairs.

NEW ZEALAND SAFETY EVALUATION PROCEDURES

The first document dealing with post-earthquake inspection in New Zealand was published in 1990 (Works 1990). A team from New Zealand had deployed to California after the Loma Prieta earthquake and used this experience to develop procedures based on the original ATC-20 document. One unique adaptation included an orange placard to provide another classification between yellow and red tags. These procedures were later updated by a group from the New Zealand Society for Earthquake Engineering (NZSEE). This document was sent to all the territorial authorities to provide a framework for post-event response planning (NZSEE 1998).

NZSEE undertook another update in 2004. Two primary issues initiated this action. First, the Civil Defence Emergency Management Act and the Building Act were revised and implemented in 2002 and 2004, respectively, providing a legal basis for the procedures. Second, the city of Auckland purchased a customized ATC-20 training package based on the original three placards, causing potential conflicts with the four-placard system. The resulting document (NZSEE 2009) became the basis for New Zealand's safety inspection process.

The 2009 document returned to the three-placard system and established minor differences in nomenclature. In lieu of the Rapid and Detailed Evaluation procedures, two types of rapid assessment were created. Level 1 corresponds to the Rapid Evaluation, and Level 2 replaces the Detailed Evaluation but is not as comprehensive. An additional issue that came from this revision is the restriction that the building safety evaluation procedure can only apply during a formally declared state of emergency (NZSEE 2011a).

Additional updates based on usage of the procedures in the 2009 Padang, Indonesia, and 2009 L'Aquila, Italy, earthquakes had been completed but were unpublished at the time of the Darfield event. The first modification is in the Level 2 usability categories prepared for the unpublished 2010 update of the NZSEE guidelines, which are shown in Table 2. These categories were developed to provide more details on structure condition. The second modification was adopted from the Italian practice of classifying a building as "unusable for

Table 2. Usability categories in 2010 NZSEE guidelines (unpublished)

Placard	Usability Category (Safety Focus)
Green	G1 - Occupiable, no immediate further investigation required G2 - Occupiable, repairs required
Yellow	Y1 - Short-term entry Y2 - No entry to parts until affected section repaired or demolished
Red	R1 - Significant damage - repairs/strengthening possible R2 - Significant damage - demolition likely R3 - At risk from adjacent premises or from ground failure

external risk only" when a normally safe building is threatened by an adjacent building or geotechnical damage. This modification is expressed in the R3 category.

CHRISTCHURCH POST-EARTHQUAKE SAFETY EVALUATION

THE DARFIELD EARTHQUAKE

At 4:35 am local time on 4 September 2010 the M_w 7.1 Darfield earthquake struck. The epicenter was approximately 40 km west of the city of Christchurch. The resulting structural and geotechnical damage was significant. Fortunately, this earthquake resulted in no fatalities. Two unoccupied unreinforced masonry (URM) buildings collapsed following a 5.1 magnitude aftershock. The buildings were located within 5 km of the epicentral distance of the aftershock (Wood et al. 2010). The emergency operations center (EOC) was established at 5:30 that morning and was staffed continuously until 17 September 2010. The official end of the state of emergency was noon on 16 September 2010. Building assessments began the day of the earthquake, and by the following morning at 6:00 am over 500 damaged buildings had been identified, of which 90 were in the central business district (CBD) (NZSEE 2011a). A cordon (fencing operation in order to limit access only to those who are participating in emergency operations) of the CBD was also established which lasted from 4–10 September 2010 (CERC 2011b).

One of the challenges in the assessment process was having a sufficient number of chartered professional engineers (CPEngs), the New Zealand equivalent of the U.S. professional engineer (PE) certification. The licensure requirement was not previously specified but was desirable for the experience and knowledge represented by the certification. In order to solve this problem, the Institution of Professional Engineers New Zealand (IPENZ) was active in finding 94 volunteer engineers from around the country who served as inspectors over the course of the emergency period. Table 3 shows the statistics of the number of buildings evaluated after the September earthquake (NZSEE 2011a). Residential structures whose primary damage was toppled chimneys and liquefaction-induced damage received a rapid assessment, including a health and welfare component, rather than the more detailed assessments done for buildings in the central business district.

Table 3. Building assessments following the 4 September 2010 earthquake (CERC 2011a)

	Buildings Inspected			
Placards	Commercial		Residential	
Green	873	71%	5498	82%
Yellow	275	22%	937	14%
Red	88	7%	251	4%
Totals	*1236*		*6686*	

The Level 2 assessments were carried out on a priority basis among the buildings that had received Level 1 assessments. The first step included all buildings in the central business district and along primary arterial routes in the following categories (NZSEE 2011a):

- Buildings with a Level 1 red or yellow placard
- Green-placarded buildings with four or more stories
- Green-placarded buildings with high occupancy capacity
- Green-placarded buildings where a Level 2 assessment had been recommended

These buildings were then allocated to one of the following categories of priority: Very High (VH), Medium High (MH), Medium (M), and Low (L). Yellow placards were assigned to the M category, and red placards were assigned L, given that the features that were perceived to render these buildings unsafe had already been identified as requiring action. The green-placarded buildings that had been identified for a Level 2 inspection were allocated to either VH or MH category. Buildings most likely to be utilized in recovery or that would result in the ability to reduce the cordoned area of the CBD were given the highest priority. The Level 2 inspection process was affected due to difficulties in gaining access to these buildings, and led to the need to repeat and validate some Level 1 assessments.

THE BOXING DAY EARTHQUAKE

The Boxing Day (26 December 2010) series of aftershocks included a M_w 4.7 earthquake that occurred at 10:30 am. The epicenter of this event was only 5 km from the center of Christchurch. Additional damage to structures occurred, although many buildings were not occupied due to the holiday season. Fortunately, there were no fatalities. A formal state of emergency was not declared, although building assessments were completed by a small party of local engineers engaged by the Christchurch City Council. This was done through the New Zealand Building Act, which allows local authorities to declare buildings dangerous and unoccupiable (CERC 2011b).

THE 22 FEBRUARY 2011 EARTHQUAKE

While not the largest energy release or longest duration of the Canterbury sequence, the triggered earthquake that occurred at 12:51 pm on 22 February 2011, centered near Lyttelton (M_w 6.2), was by far the most damaging. Dozens of commercial buildings collapsed or partially collapsed. Additional geotechnical damage occurred in the form of liquefaction, landslides, and rockfalls. The state of emergency was officially declared the following day, the same day that planning was taking place for the post-earthquake assessment program. An emergency operations center was established as it had been following the Darfield earthquake to coordinate response. Due to the damage, the central business district was evacuated and cordoned to limit access only to those assisting in event response. A major Urban Search and Rescue (USAR) operation was conducted to search for the injured and dead in the rubble. The experience from September led to a more effective initial plan for what would be the largest effort in building assessments. One of the critical parts to this plan was to mobilize qualified CPEngs, especially those who participated previously in the assessment process. The process of bringing volunteer engineers from other areas of New Zealand continued for several

Table 4. Building assessments in Christchurch following the 22 February 2011 earthquake (Canterbury Earthquake 2012).

	Assessment placard			
Building type	Red	Yellow	Green	Total
Commercial	977	1,093	3,221	5,291
CBD	1,058	1,005	2,253	4,316
Residential	1,776	Not assigned[a]		60,951
Heritage	377	Not available[b]		1,086

[a]Residential structures were assigned either a red placard or a leaflet in lieu of a green or yellow placard.
[b]The data on green and yellow placards for heritage buildings was not available at the source of this data.

weeks. Several engineers, locally and from around New Zealand, volunteered multiple times over the course of the effort.

The assessments continued through the end of March 2011. On or around 15 March 2011 the Christchurch City Council started contracting the assessment work to consulting engineers due to the challenge of finding volunteer CPEngs. A total of 71,644 buildings in Christchurch were assessed between 23 February and 4 April 2011, as shown in Table 4. The data for Table 4 was gathered from the public notices, which have now been archived (Canterbury Earthquake 2012). A total of approximately 130,000 buildings were assessed following the February event in Christchurch and the surrounding areas (CERC 2011a). Due to the increased inspection-related demand following the February 2011 earthquake, assessment activities were organized as several separate focused operations such as Operation Cordon and Access, Operation Suburbs, Operation Demolition, and Operation Critical Buildings. Each of these operations, including rapid response teams, indicator buildings, and risk assessments for demolition of red-tagged buildings, is discussed below.

The afternoon of 13 June 2011 brought two additional damaging aftershocks. A M_w 5.5 occurred at 1:00 pm followed by a M_w 6.0 at 2:20 pm. Several buildings within the central business district experienced further damage or collapse; additional liquefaction, landslides, and rockfalls occurred in the hills surrounding Christchurch. One elderly man died after being knocked unconscious by falling debris (GNS 2011). No state of emergency was declared, but engineers in the employ of the Canterbury Earthquake Recovery Authority (CERA) and the Department of Building and Housing (DBH) performed assessments of buildings within the central business district to identify structures that had either become more critical or were now dangerous due to the aftershocks.

UNIQUE ASPECTS OF BUILDING ASSESSMENT OPERATIONS AFTER THE 22 FEBRUARY 2011 EARTHQUAKE

As the February event resulted in the most damage and greatest need for post-earthquake assessments, several unique aspects of the procedures used by the Christchurch City Council are discussed in more detail, including the task-specific operations, selection of indicator buildings, and the use of rapid response teams.

OPERATION CORDON AND ACCESS

Due to the large amount of damage in the central business district following the February earthquake, the decision was made to cordon off the district for safety and security reasons. The cordon operations included fencing the central portion of the city with entry allowed only for official business. One of the challenges with the cordon was an appropriate entry control method (i.e., credentials or access pass) to allow only those on official business to enter.

The Level 2 inspection process required entry into potentially unsafe buildings. This operation was carefully controlled by the emergency operations center in which safety personnel (similar to the USAR members but trained for basic safety and rescue operations only) were attached to each engineering assessment team. Any time an unsafe building was entered, only one engineer and one safety personnel could enter while the others remained outside so as to serve as a communication link with the EOC. Professional locksmiths were employed to open doors and allow inspectors to enter secured buildings. When Level 2 assessments had been completed and all exterior hazards had been removed or cordoned off in a certain section, that section was then opened.

Each team was required to send text messages at regular intervals to provide the EOC with status updates and safety verifications. Another ongoing task within the central business distrct was removal of vehicles that had been stranded in parking garages. Some assessment teams were responsible for evaluating the garages and determining the safest routes for vehicles to be removed from multistory parking structures.

OPERATION CRITICAL BUILDINGS

In the first few days and weeks after the earthquake, teams of specialists were established to focus on evaluating safety and developing interim stabilization measures for 40 major damaged midrise buildings in the central business district. Several of these buildings were initially considered at risk of collapse and others had damage that could not initially be judged based on Level 1 inspections. Their risk of collapse in some cases impeded the safety assessments and recovery of smaller buildings nearby. Operation Critical Buildings teams visited the buildings, reviewed drawings made available by the Christchurch City Council building consent authorities, and attempted to judge the extent and seriousness of the damage before rendering Level 2 inspection assessments and emergency stabilization advice. While these Detailed Engineering Evaluations are more typical of assessments ordered by building owners, the hazard many of these buildings posed to other buildings was significant enough to merit this action by the EOC. It should also be noted that New Zealand in general has a comparatively open policy on sharing technical data as it pertains to legal issues and possible litigation. In the United States more restrictions on the availability of drawings may be encountered due to legal and security constraints.

OPERATION SUBURB

The large number of residential structures, typically one-story wood-framed structures, damaged due to both structural and geotechnical effects necessitated an enormous effort. Operation Suburb began on 24 February with 40 teams consisting of engineers, building inspectors, and welfare officers visiting many of the suburbs surrounding Christchurch. The operation had a specific goal of assessing residences throughout the damaged area.

The welfare officers were utilized to assess the emotional state of citizens as well as whether housing or financial assistance was required. A Level 1 assessment was carried out for all residences while a Level 2 assessment was carried out only if evidence of significant damage was found. For the residential assessment, yellow and green tags were replaced by a white leaflet informing owners that the building had been inspected and was not considered hazardous. The leaflet did encourage building owners to hire a structural engineer to do a more detailed inspection. The red tag was still utilized for unsafe structures. Residential assessments accounted for over 90% of the 130,000 assessed buildings.

OPERATION SHOP

Operation Shop started the same day as Operation Suburb; however, only five teams consisting of an engineer and building inspector were deployed. The purpose of Operation Shop was to quickly get priority suburban commercial buildings assessed so these facilities could be opened to serve the public. These included malls, grocery stores, hardware stores, medical clinics, and pharmacies.

OPERATION DEMOLITION

Due to the significant danger posed by many severely damaged structures, the need to demolish structures to allow access to roads and otherwise safe buildings prompted Operation Demolition. The primary avenue for determining whether buildings needed deconstruction or demolition was the assessment team. During Level 2 assessments, any building receiving a red placard also required a blue risk assessment form. The primary information needed for the form included details of the structure, evaluation of the risk to other structures or public areas, and overall building damage classified by percentage. The exact content of the form evolved throughout the process.

As of 26 June 2012, 1,058 buildings had been identified for demolition (226 of them heritage buildings), which included total demolition, partial demolition, and make-safe categories (http://cera.govt.nz/demolitions/list). Each building that was demolished had gone through review by the Civil Defence National Controller prior to April 2011. Subsequent reviews were done by the Canterbury Earthquake Recovery Authority (http://cera.govt.nz/demolitions/). The large number of demolitions may have been influenced by the very high level of earthquake insurance in New Zealand. In countries with less insurance, there may be less motivation to demolish and instead repair buildings. Reportedly, the insurance money in New Zealand is not sufficient for the necessary repairs, however, so the owner chooses to take the settlement money, demolish, and rebuild at a later date. This option is chosen as some occupants may have concerns with the expected performance of a repaired, damaged building and the owner prefers a new building.

RAPID RESPONSE TEAMS

Rapid response teams were assigned at the beginning of each day. The teams had the same composition as other assessment teams. In lieu of having an assigned group of buildings to assess, these teams were placed on call in the emergency operations center. Citizens in need of engineering services could call the EOC and request the services of an evaluation team. Subsequently, the rapid response teams would be sent. Most calls were by owners of residences or small businesses seeking to determine the status of their building, which may not have been inspected previously. The rapid response teams were also used in some cases to allow owners or tenants to enter damaged buildings to retrieve critical belongings. For these cases, the engineer and USAR personnel would complete a Level 2 inspection and make a decision as to how long the owner could remain inside the building and the areas within the structure that were accessible. The engineer and USAR personnel would then accompany the owner throughout the process. Close communication with the EOC was maintained throughout the process of entering possibly dangerous buildings.

INDICATOR BUILDINGS

Following the September earthquake, there was an increasing concern about progressive collapse of partially damaged and structurally weakened buildings during the subsequent aftershock activity. However, due to the frequent aftershock activity it was not possible to reinspect all buildings after each such tremor. This necessitated clear criteria for reinspection, which were formalized following the February event (NZSEE 2011a). Eight buildings were selected to include representative samples of building types (e.g., unreinforced masonry bearing wall, reinforced masonry shear wall, reinforced concrete shear wall) and damage thresholds (damage exceeding certain threshold triggers reinspection). An additional criterion for buildings selection was the level of damage. The selected buildings should have incurred some damage but not so extensively that a relatively small aftershock would cause disproportionate additional damage. After any strong aftershock, the eight buildings were reassessed specifically to determine whether further damage had occurred. Based on the response of the indicator buildings, a reinspection of similar nearby buildings would be required. Each morning, specific evaluation teams familiar with the selected structures were assigned to be deployed to the indicator buildings in the event of an aftershock. The objective was to assess potential damage to indicator buildings and follow consistent procedures, including photographic documentation to monitor damage, if any, between different visits.

TRANSITION TO RECOVERY

The state of emergency was lifted on 30 April 2011. The Canterbury Earthquake Recovery Act (CERA) took effect 18 April 2011. One provision of this act was to extend the life of the posted placards by 12 weeks, to 12 July 2011. To address this issue, CERA engineers posted notices on buildings to replace the previously applied red and yellow placards. Information was also provided to building owners. The first was a four-page pamphlet, “A Guide to Structural Assessments and Repair Work” (CCC 2011), which gives general information about the process and requirements of the recovery act. The pamphlet states that a building with structural damage may require an upgrade in accordance with the 2004 Building Act, which requires the building be strengthened to 33 percent of the New Building Standard with a recommendation of 67 percent. A second publication, from the Department of Building and Housing (DBH), provided additional information about nonresidential and multiunit residential properties in greater Christchurch (DBH 2012a). Information was also provided to engineers involved in building repair or renovation following the earthquakes. The Engineering Advisory Group of the DBH provided a guideline on detailed engineering evaluations of structures (EAG 2011). More recently, guidance has been provided to engineers assessing multiunit residential and nonresidential structures in greater Christchurch (DBH 2012b).

LESSONS LEARNED

As with any significant undertaking, there was a combination of successes and areas in need of improvement. Overall, the most important lesson is that the post-earthquake evaluation process is critical to response and recovery and must be well coordinated, include quality assurance, and use qualified professionals. Other specific lessons learned throughout this process are listed below. It should be noted that many of these lessons have been included in an update of the California Emergency Management Agency's *Safety Assessment Program Coordinator Student Manual Version 5* (Cal EMA 2012).

- It is critical to clarify the intent and applications of the placard system. Some of the buildings that collapsed catastrophically in the February aftershock were originally assigned a green placard after the September 2010 earthquake. The safety assessment program received some criticism from the public due to the confusion. An "Inspected" placard does not mean the building is safe against future earthquakes, only that the lateral load capacity is not significantly diminished. Building safety is always the responsibility of the building owner. This information must be clearly communicated to the public.
- Availability of structural drawings was critical in carrying out search and rescue operations following the February 2011 earthquake. Similarly, Operation Critical Buildings benefited significantly from the availability of structural drawings. Building department administrators should consider developing and maintaining digital archives and institute document-retrieval procedures for information about major buildings and other facilities in their jurisdictions. An electronic database containing drawings and other relevant facility information would be a valuable tool for engineers and emergency personnel responding to disasters. It was also discussed that the repository for a city should be located elsewhere but within reasonable proximity (i.e., the data for San Francisco stored in Sacramento). In the United States, there are many significant barriers (final versus as-built drawings, electronic versus paper drawings, plan ownership and privacy, limited governmental resources) to creating such a database.
- Field equipment, such as placards, caution tape, forms, pens, staple guns or package tape, etc., should be broken down into backpack-sized units set up to supply one team for five days of inspection. Only permanent-ink markers should be used for the placards since rain and sun can render writing illegible.
- Inspector strike teams should be organized to clear specific occupancies, with each team tasked to serve specific types of construction or specific building functions to ensure safety and efficiency. For example, certain teams of structural engineers could be used to inspect high-rises, others would evaluate essential services facilities, still others low-rise apartment buildings. Likely, most teams would be looking at one- and two-family residential buildings. This approach would be useful particularly for catastrophic earthquakes, as it addresses prioritized sectors of the community speedily. Each of the teams would require members with different skillsets.

- Among the essential facilities for early safety assessment, certain occupancy types such as pharmacies, grocery stores, hardware stores, water treatment plants, and wastewater treatment plants should be given priorities for inspection. Addressing these types first allows the public to gain access to medicine, food, bottled water, and repair supplies with less delay. Assuring the availability of safe drinking water and operational wastewater and sewer systems improves public health.
- The damage assessment process should make use of indicator buildings of various construction types to manage the effects of aftershocks. If buildings of a certain construction type showed excessive damage in a given aftershock, then all buildings of that type nearby should be reexamined. The challenge is to ensure that buildings are selected with similar height, site condition, structural system, construction period, and appropriate damage level so that the post-aftershock assessment results are meaningful. Otherwise, either too many or too few reassessments would result.
- Strong motion instrumentation programs should institute emergency plans and establish funds to enable the rapid installation of instruments inside indicator buildings as well as nearby sites on the ground after initial earthquakes to facilitate rapid assessments of aftershock effects.
- To ensure the safety of inspectors, a periodic check-in with the assessment program coordinator every 90 minutes or two hours by phone call or text message is essential. This check-in could also be used as an opportunity to provide a quick progress report, if time allows.
- If the impacted region includes a large number of heritage buildings (commonly referred to as historic buildings in the United States), representatives from the heritage building community should be engaged in advance of future earthquakes to establish a process by which these types of buildings can be evaluated for safety while considering the historic nature of the structures.
- Clear communication to the public is critical. It is recommended that widely distributed public notices that can be updated as the situation changes include the following: how to arrange for help to enter unsafe buildings for possession retrieval; general information on disaster recovery, including the building department's standard procedures; how to have a red or yellow tag changed to a green tag by abating the hazards through repair; and reoccupation of green-tagged buildings with only a Level 1 or Rapid Assessment.
- Engineers must be properly trained before becoming inspectors. After the Darfield event, many inspectors automatically assigned unreinforced masonry buildings a red tag because of their construction material and not how the building performed in the earthquake. Due to this, many of these buildings had to be reassessed and many were green-tagged. This resulted in lost effort and building owners being unable to use buildings that had survived the earthquake with minimal damage.
- Legislative authority is needed to enable lawful removal and placing of placards on buildings after the emergency period. New Zealand's Building Act currently only allows placarding during a state of emergency. Removal and change of placards is not clear under current legislation in New Zealand. This presented a significant challenge at the end of the emergency declaration following the February 2011 event. The Canterbury Earthquake Recovery Act was interpreted to permit continued tagging, but it was acknowledged that a more broadly applicable approach is needed in

the future. Similar gaps in enforcement exist in many jurisdictions throughout the world. For example, the lack of enforceability of safety assessments has been identified as a major legal gap in most jurisdictions throughout the United States. The California Building Officials organization strongly recommends that local governments enact a model placard adoption ordinance so that placards are recognized as an official and enforceable act of the jurisdiction regardless of the timing of the emergency period (CALBO 2012). Many local jurisdictions have done so.

- The immense amount of data generated by the assessment teams (digital photos and assessment forms) should be placed in a centralized and functional repository that is able to archive data in near real time. This would make the data available to the recovery process and also later on as researchers study building performance and process the data. The repository framework needs to be in place prior to the event so it can be mobilized quickly once the assessment operation begins. The primary challenges and barriers will be determining who should be responsible to create, operate, and maintain the database and who will have access to the database both during building assessment operations and after operations for research.

CONCLUSION

Building safety assessments are resource- and labor-intensive but have a tremendous impact on earthquake response and recovery. The September 2010 earthquake, which had lesser impact in the central business district, provided a foundation for the organization of a significant building safety inspection program in Christchurch and to institute the necessary framework, which was required after the February 2011 earthquake. The NZSEE safety assessment procedures, which are based on ATC-20, were effectively used throughout the Canterbury sequence. Several unique and effective procedures were instituted following the September 2010 earthquake that were further streamlined during response planning before the February 2011 earthquake. More will be learned as time goes by and as the recovery continues. Many of these lessons learned can and should be used to ensure that response to and recovery from future events will be better facilitated.

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