Recovery and Resilient Design for the Future – a Case Study from Christchurch, New Zealand

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ABSTRACT
The city of Christchurch on the east coast of New Zealand's South Island experienced multiple major earthquakes starting in 2010 and peaking in 2011 centred on the city. Widespread damage occurred to properties, infrastructure and roads. In the six years since, significant work has been undertaken to recover from the disaster, much of which is ongoing. The south of the city extends up the flanks of the extinct Lyttelton Volcano. The steep north-facing basaltic slopes have various cliffs and many suffered significant collapses during the earthquakes. Additionally, large quantities of boulders were released from the many rock outcrops above residential areas. A vast amount of geotechnical information was gathered, analysed and used by the government in the subsequent hazard zoning of the land across the city.

This paper describes the early emergency response and recovery work undertaken by the Canterbury Earthquake Recovery Authority (an agency formed in response to the earthquakes by the New Zealand Government) and the engineering community. The wider recovery efforts are briefly described, particularly the implications of the land zoning on future events and the robustness of the engineering designs to provide resilient solutions to withstand future earthquake events.

The paper discusses engineering implications of the zoning using a case study of the key cliff collapse and large mass movement area. Shag Rock Reserve, located in Sumner, is a local reserve area with an 80m high historic sea cliff, at the western end of which lies the Deans Head landslide comprising 50,000m^3 of soil at risk of landslide failure. The basaltic cliff receded approximately 20m horizontally during the major earthquake events, and the landslide cracks totaled >1.5m. The project to reduce the risk from cliff collapse and mass movement to the lifeline road below, required close collaboration between the Christchurch City Council and the Canterbury Earthquake Recovery Authority, local iwi (indigenous tribes), engineers, project managers, the city's infrastructure rebuild team, insurance companies, local businesses and various other stakeholders.

1 INTRODUCTION

1.1 Background

Christchurch City is on the east coast of New Zealand's South Island. The 2010/2011, Canterbury earthquakes began on 4 September 2010 with a M7.1 earthquake near Darfield, 40km west of the City. On 22 February 2011, a M6.3 earthquake occurred under the south of the City and a M6.4 earthquake on 13 June 2011 under the southeast of the City. A fourth earthquake, M6.0 on 22 December 2011 occurred 9km to the east of the City, refer to Figure 1. The earthquakes are referred to in this paper as the 'September', 'February', 'June' and 'December' earthquakes.

There was minimal slope instability in the Port Hills from the September earthquake because the epicentre was 40km away; however, widespread rockfall, cliff collapse and landslides occurred during the February and June earthquakes. The December earthquake caused limited further instability.

1.2 Geological Setting

Christchurch City is located on the Canterbury Plains, an area of glacio-fluvial gravels overlain by deep alluvial deposits laid down over the last 3Ma (Forsythe et al 2008). The greywacke bedrock is several hundred metres below Christchurch. Covering an area of approximately 120km^2, the Port Hills lie to the south of the City, they are part of the eroded flanks of the extinct Lyttelton Volcano, refer to Figure 2. The geology comprises interbedded basalt that has columnar jointing, ash layers, and layers of breccias and agglomerates. The columnar basalt is very strong, the ash is very weak, the breccia layers are variable in strength, and the overall rock mass is dilated. Overlying the rock are thick deposits of loess (wind-blown silt) which generally thicken to the west. The topography of the Port Hills is generally more rugged to the east with steep slopes, numerous rock bluffs and cliffs.

1.3 Rockfall

Extensive rockfall occurred during the February and June earthquakes. In total over 8,000 boulders were mapped over the Port Hills area. The mean size was 0.7m^3 (approximately 1.75 tonnes), however the largest was estimated at 35 tonnes. Many houses were inundated with boulders; some had boulders that went through the house and continued down the hill below. Others had multiple boulders land inside the house and garden, the greatest accumulation observed had 6 boulders in the house and 45 in the garden.

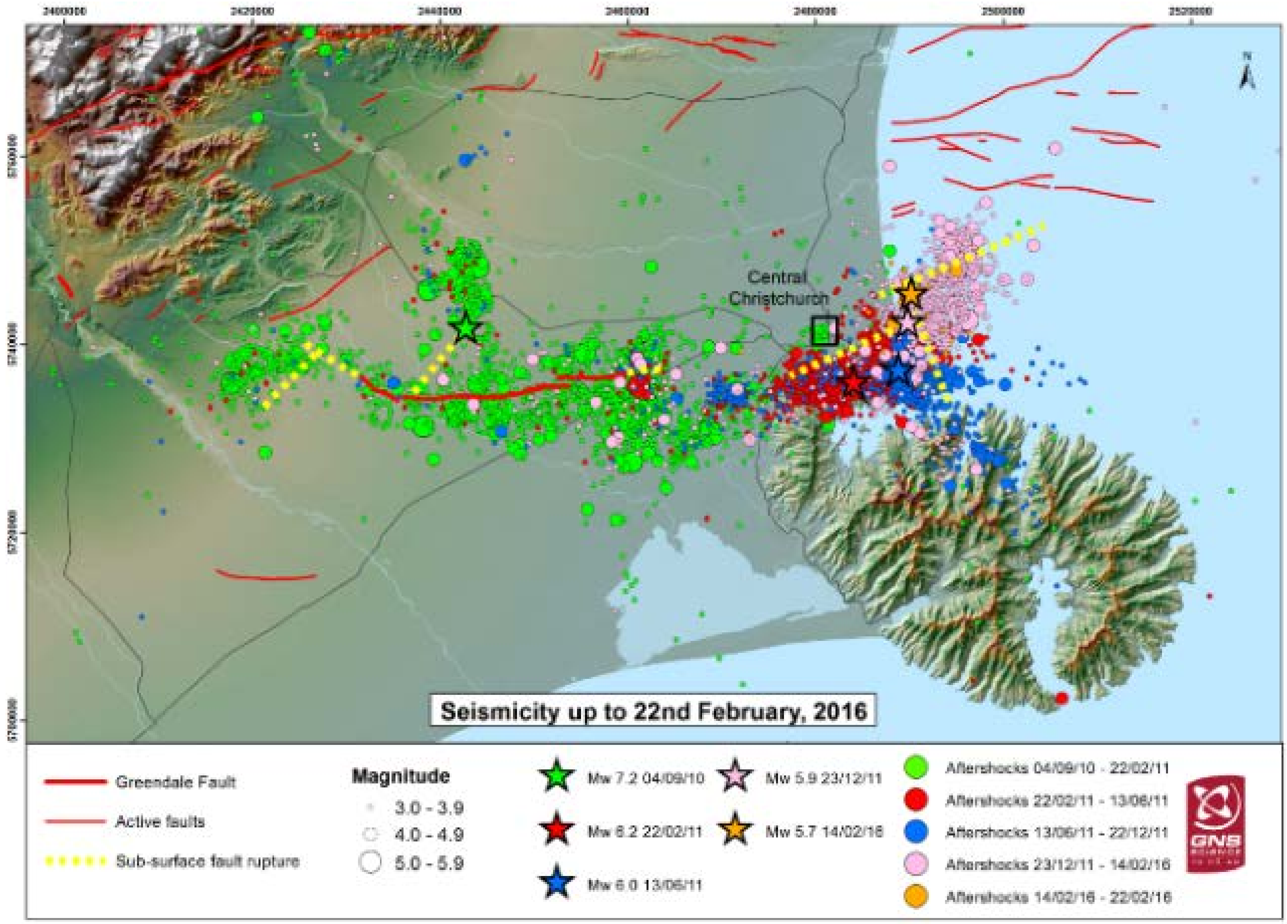

Figure 1. Map of the Seismicity in the Canterbury region up to 22nd February 2016 (GNS)

Figure 2. Topographic map of the Port Hills to the south of Christchurch

1.4 Cliff Collapse

During the February earthquake, significant cliff collapses occurred and mapping was undertaken to determine whether areas of potential future failures could be defined. Detailed mapping along cliff tops showed a zone of cracking generally 10m to 40m back from the cliff edge.

The majority of cliff collapses (by volume) occurred later in the June earthquake where up to 15m was lost from the cliffs. The mapping that had been done prior to the June earthquake was revised following the earthquake as new cracks had formed and many existing cracks had increased in size. The new location of the cliff edges were often observed to be where hairline cracks were mapped following the February earthquake. This example emphasises the importance of carrying out field observations as soon after an event as possible.

1.5 Landslides

The initial work undertaken comprised a walkover survey of the most significant landslides where a rapid assessment was made of their stability. Crude but effective monitoring devices were installed at that time. The most significant landslides were intensely monitored by surveyors. For example, one area of 1.3ha called Deans Head had cracks up to 0.5m wide and up to 1.5m deep, marking the scarp of a large landslide, which threatened many houses and a main lifeline road, the only access to the eastern suburbs of the Port Hills. It was soon understood that the landslides were not creeping but only moved with significant seismic activity and as such long term monitoring with real-time GPS was installed.

2 THE ORGANISATIONS

Many different organisations have been involved in the recovery of the Greater Christchurch Area, a brief summary is listed below :

- CCC – Christchurch City Council
- CDEM – Civil Defence Emergency Management
- CERA – the Canterbury Earthquake Recovery Authority, the New Zealand Central Government agency that was set up to manage the Recovery.
- Ngau Tahu – the representative organisation for the local indigenous tribes
- EQC – The Earthquake Commission, a Government-owned Crown entity that provides primary natural disaster insurance to the owners of residential properties in New Zealand.
- All the private insurance companies
- GNS – Geological and Nuclear Sciences, the Crown Research Institute
- IPENZ – Institute of Professional Engineers, New Zealand
- USAR – Urban Search and Rescue

3 EARLY EMERGENCY RESPONSE

The government declared a National state of emergency in February 2011. The emergency operations centre was run by CDEM teams and included operational activities from other specialist teams such as USAR. The focus was initially in the lifesaving/rescue phase, which was largely in the city centre, where most of the fatalities occurred. The overall operational response then transitioned from rescue into response (demolitions etc) and eventually into the recovery phase.

In the Port Hills, the geotechnical response was unique. In the months following the February earthquake, several private consultancies formed a subject matter expert team - the Port Hills Geotechnical Group (PHGG); they worked in a collaborative (not commercially competitive) manner, dividing the Port Hills area up into different segments that were geotechically monitored and managed in the same way. The culture within the PHGG evolved naturally, it was not "planned" but due to the extreme circumstances, all members ignored the label of their parent organisations, freely shared intellectual property, resources and through collaboration, identified and managed the hazards using a consistent framework across the Port Hills. This is one of the many unsung success stories of the technical response to the earthquake event.

The initial emergency response across the city comprised issuing of "stickers" denoting the building status onto each building. These follow a 'traffic light' approach of red (building is not to be entered), yellow (restricted entry), white/green (no restrictions on entry). The stickers can only be issued under the authority of the Civil Defence Controller and legally only apply during a state of emergency. After the National state of emergency was terminated in April 2011, many residential properties were still at risk from geotechnical hazards and as such, the red stickers were replaced with prohibited access notices by CCC under Section 124 of the Building Act (s124). Typically, these notices are only issued to unsafe (structurally compromised) buildings. Many of the buildings in the Port Hills were structurally sound however, and the legislation of the building act had to be amended by Order in Council to allow the issuing of s124 notices to include hazards beyond the property boundary. These circumstances were anticipated when the current Building Act was written, but lessons learned from this event have been sent to the relevant legislation.

4 RECOVERY

4.1 Canterbury Earthquake Recovery Authority

Central government created CERA on April 18 2011. CERA was the Agency responsible for leading and coordinating the recovery of Christchurch. The creation of a central government agency with a distinct local focus created some interesting circumstances. The intent was for the agency to run for 5 years, and amongst other obligations, it had to develop plans for other agencies to implement as it scaled down. CERA used the Canterbury Earthquake Recovery (CER) Act 2011, which contained particular specific legislative powers to enable an effective, timely and coordinated rebuild and recovery effort. CERA's role, comprised the following:

- Provide leadership and coordination for the ongoing recovery effort.
- Focus on economic recovery, restoring local communities and making sure the right structures are in place for recovery.
- Enable an effective and timely recovery.
- Work closely with Te Rūnanga o Ngāi Tahu (the tribal authority of the main Māori iwi (tribe) of the southern region of New Zealand) and the local and regional councils.
- Engage with local communities of greater Christchurch, the private sector and the business sector.
- Keep people and communities informed.

- Administer the CER Act.

During its initial establishment, whilst the country was still in a state of emergency, CERA worked closely with Civil Defence and various early recovery organisations. Due to the disruption to all the "normal" authorities such as the council core business etc., CERA took control of the majority of the early recovery effort. Over time CERA expanded its role as the recovery progressed then gradually handed back leadership of all aspects of the recovery to other local and central government departments, agencies and organisations to enable the recovery work to continue for as long as it was required.

4.1.1 Land Zoning

From a geotechnical perspective, the key role CERA took early on was to zone the residential parts of the city 'red' or 'green', based on the risk from geohazards, which were primarily liquefaction, lateral spreading, rockfall, cliff collapse and landslides. The level of acceptance of risk was determined based on the risk to life from the rockfall and cliff collapses in the Port Hills and the likely level of future disruption from the liquefaction and lateral spreading hazards on the flat land. The identified risk levels or potential for future land damage determined the red and green zones, respectively.

The Government's aim of the zoning was ultimately to provide exit options for the landowners in those parts of the hills that, due to unacceptably high geotechnical risks (primarily rockfall and cliff collapse) were unsafe to be occupied by residential properties or commercial premises in the long term.

The zoning model in the Port Hills was very complex and went through several iterations before the finalised version was released. The decisions relied on two key sources of information, in addition to the field observations. The first was a life-safety risk model produced by GNS. The model inputs comprised mapping of the majority of the boulders that fell during the earthquakes, in association with many 2-D rockfall risk models along observed and anticipated trajectories (this work was undertaken by GNS and PHGG). Due to the vast data set of over 8,000 mapped boulders, the modelling replicated the observed run-out distances and bounce heights with a reasonably high level of accuracy. The second piece of information was a 3-D rockfall model across the same Port Hills area, undertaken by a private contractor, with technical support from experts in Switzerland and Italy. The two models were commissioned separately, one for the CCC and one for CERA. When the two were compared, the results were similar, the models disagreed in only a few parts of the Port Hills and these were generally the areas with intricate and complex geomorphology and/or geology.

With the rockfall models confirmed, GNS calculated the risk in terms of the Annual Individual Fatality Risk (AIFR) from the probability (likelihood) that a particular person will be killed by rockfall in any year at their place of residence. Risk maps were produced shading areas within an order of magnitude to create five risk categories ranging from $>10^{-2}$ to $<10^{-5}$. In line with international best practice on exposure to risks, CCC and CERA adopted the stance that a risk greater than 10^{-4} was unacceptable and those properties at unacceptable risks were zoned 'red'.

The residential properties that were zoned 'red' received an offer to purchase their property from the Crown (via the NZ Central Government acting as the Crown's agent) with three basic options:

- Option 1 - The Crown would buy the house and the land, and keep the proceeds of any insurance claim
- Option 2 - The Crown would buy the house and land with the owner retaining the insurance claim over the building
- The resident could choose to retain ownership of the property (with the assumption that the owner knew that they may not be able to reinsure or re-build on it)

The intent of this policy was to provide an efficient way to provide people with options for managing their exposure to the hazards. This sounds relatively straightforward; however, there was the added level of complexity with the existence of the Earthquake Commission. For all related insurance claims made after the earthquakes, an EQC claim is also made and EQC covers the first $100k portion of any claim, anything over and above this reverts to the private insurance company. For many people this meant dealing with at least EQC, their private insurance company, valuers, loss adjusters, contractors and a range of local and central government agencies.

4.2 Political Oversight

The political imperative was to provide certainty to property owners and a swift way out of an immensely complex and contractor restrained repair market.

In the "flat lands" (the majority of Christchurch to the north of the Port Hills), over 7000 houses were zoned 'red' and many thousands of houses around them were extensively damaged. Had the government not stepped in – large parts of these neighbourhoods would have been subject to decades of un-coordinated demolition, construction activity, road repairs, dust, noise and vibration. This would have come with extensive and multi-hazard health and safety issues and was therefore considered the least preferable option.

In the Port Hills, 711 properties were red-zoned. Of these, approx. 90% had buildings on them and 95% were residential. 620 owners accepted the crown's offer to purchase the house and the land and the crown therefore assumed the obligation to manage the properties. This involved demolishing the houses and then managing the land in the interim until decisions were made over the long-term management.

In order to ensure the clearance works were managed in logical and safe sequence, CERA established an operational arm that managed the interests of the crown, took a leadership position on health and safety and ensured that stakeholders were informed of plans and consulted where possible. CERA in some circumstances agreed to take over insurer lead demolitions as the complexity, risks and stakeholder management obligations were more appropriately lead by a government backed delivery team.

As a new activity for the crown, this work evolved rapidly with a number of lessons learned along the way. For example:

- Large and complex worksites will develop their own culture very quickly,
- People perceive risk in widely different and changing ways,
- The ‘honeymoon’ period after a disaster dissipated very quickly, and
- Dealing with stressed, confused and angry people takes skills that are in short supply.

This work was challenging and tested the diplomacy and communication skills of the engineers. The interaction between logic (engineering) and reality (emotive) was fascinating, challenging and hugely time consuming.

5 DEANS HEAD AND SHAG ROCK RESERVE

Several properties were located at the edge of cliffs that had experienced large failures, one in particular, Shag Rock Reserve, an old sea cliff, it is 80m high and had retreated by 15m in the June earthquake alone, this had caused the collapse of one of the properties that had been built around 15m from the edge of the cliff. Between the February and June earthquakes, a combined total of 70,000m^3 material fell from the cliff. The main road below was at risk from rockfall inundation, however it is a key lifeline route and had to remain open. A row of ballasted shipping containers was used as a rapid protection measure for the road. These were 40ft containers with 20t ballast, with a second row on top of empty containers. The two levels were connected with shipping grade locks, refer to Figure 3. The shipping containers were used in many places around the Port Hills to protect roads from the risk of rockfall. Likewise, in the centre of town, shipping container “walls” were put up to protect road users from the risk of collapsing facades.

Figure 3. Shag Rock Reserve photographs taken in March 2011 and July 2011. Note the row of double stacked shipping containers protecting the road from rockfall

The western end of Shag Rock Reserve is Deans Head, this spur of land slopes steeply (40°) down towards the road below, refer to Figure 3. During the earthquakes, there was intense ground cracking observed and although no defined “toe” was observed, it was clear the hillside was a large mass movement area. The geology of the hillside comprises around 4-6m of Loess and Loess-colluvium soils overlying Basalt. Ground investigations were undertaken, inclinometers and piezometers installed and continuous GPS points were set up on the surface to monitor any movement. The ground only displayed significant movements during large aftershocks. GNS undertook slope stability modelling and determined that if the soil was saturated and then experienced a 1 in 10 year rainfall event, a large failure could be initiated that would inundate the road below. Just the other side of the road is the estuary and the modelling indicated that around 40,000m^3 of material could inundate the estuary. This would have significant knock-on effects to the low-lying estuarine residential areas, particularly on a spit 500m across the other side of the main channel, refer to Figure 4.

Given these potential consequences and the feasible likelihood of the slip occurring, CCC and the government determined that remediation must be undertaken. The risk to the road had to be managed, in order to do so the preferred solution was to remove the soil from the hillside, thus removing the hazard and ensuring long-term risk management to the lifeline road below during a future rainfall/seismic event. The solution, which required removing approximately 40,000m^3 of soil from the hillside in the area of the mass movement hazard, also required all the houses to be removed or demolished.

Much of the area was part of the red-zone; however, there were some properties that would be affected by the remedial works that were green zoned and therefore CCC purchased (voluntarily) the properties in order to enable the mass earthworks solution to commence.

Figure 4: Map of Shag Rock Reserve

It was unknown exactly how much soil there was to remove. The payment to contractors for many earthworks contracts are agreed based on material volumes which are generally known at the start of the project. The contract for this project was therefore agreed based on the volume of soil removed from the hillside. Again, this would normally be relatively straightforward with a topographic survey at the start and again at the end. The hillside to start with though was very densely covered with vegetation, houses, retaining walls, driveways, garages etc. and this made gathering data for a comprehensive topographic survey very difficult. Recent LiDAR data was available, however due to the dense vegetation this was also not reliable enough as a basis for the volumetric payment claims. The solution was to use traditional survey methods in combination with the LiDAR survey to start with. Using Aurecon's drone and photogrammetry methods, we soon started creating detailed, survey controlled digital models, which when compared with the LiDAR, matched very well. Throughout the course of the earthworks project, the drone was flown every week and the models compared with the previous week to track the volume of material removed from site. At the end of the project, once the hillside was cleared and a rock slope remained, the final drone model was independently checked with terrestrial survey to confirm the accuracy was comparable to traditional survey methods, although the density of the data was far greater. The drone models comprised a point cloud, when the points were joined to create a mesh, the model surface could be seen. The points were generally around 8-9mm apart. The data for this was collected in less than 1 hour and processed over night to create the model in the morning. If a terrestrial survey were undertaken for the site at the same resolution, the team would have taken weeks to complete the work

The clients for the project recognised the additional level of precision that the UAV brought to the project and the volume modelling and were happy to pay for the flight costs in order to have superior quality and more timely reports.

The second part of the project was to construct a permanent barrier to protect the road at the base of the cliff from the risk of rockfall. As the cliff was adjacent to Deans Head, the fill removed from Deans Head was used to construct a large, three benched, 10m high bund adjacent to the road with a large trench behind it, at the base of the cliff. The future resilience of the design was very important to the client and the design provides capacity for two more, large cliff collapse events.

The cliff had a large amount of loose material in the face and the health and safety of the workers and road users was the most important aspect of the whole project. There were three key monitoring systems used to manage the health and safety over and above the normal health and safety site procedures.

5.1.1 Laser scanning of the cliff face

The cliff was 80m high and approximately 400m long. A laser scanner was set up at a position to be able to measure most of the face area. The scanner was run every night across a series of defined sectors. The scan data was manually reviewed each morning prior to work commencing on site, refer to Figure 5. Scanning was undertaken during the day of the particular segments above the work areas.

Scanning was undertaken during the day of the areas of the cliff above the parts of the site where the work was being undertaken. The scans were manually checked during the day. The laser scanning approach did not provide a real-time alert system, however it was deemed that the system might provide some warning if blocks were beginning to move due to non-seismic triggers.

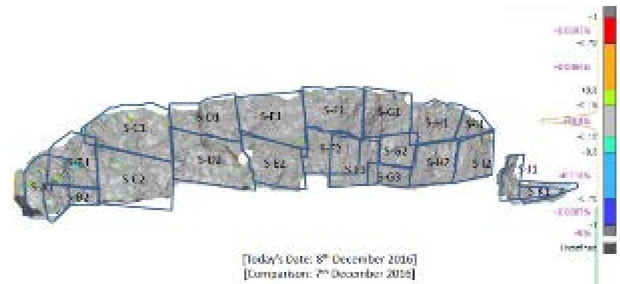

Figure 5. Laser Scan change model

5.1.2 Automated theodolite monitoring prisms on Deans Head

The Deans Head mass movement area could be monitored in near-real time. We established a monitoring point across the estuary where an automated theodolite was installed. The theodolite continually monitored up to 50 reflective prisms that were installed across the area. These were positioned in areas of particular concern, on retaining walls and properties prior to demolition; several were also installed on posts in the ground. By spreading the prisms around in this manner, we hoped to monitor localised failures of structures in addition to possible further movement of the mass movement area as a whole. The system was accessed remotely with the live signal from the theodolite transmitted back to the office via a radio transmitter. The system was also linked to an emergency text message alert system so that if there was greater than 100mm of movement the engineering geologists were alerted.

5.1.3 Tell tail monitoring of cracks at the cliff edge

In addition to the surveying approach, there were also tell-tails installed across cracks on the top of the cliff, refer to Figure 6. There were two potential failures features in the upper half of the cliff; one was estimated to be approximately 500m^3, the other about 2000m^3. These two features were measured specifically with the laser scans in detail, however during the weekly drone flights the tell tales were checked using the drone. This provided a fail-safe check if the supporting technology failed for any reason.

5.1.4 Defined no-go zones and Remote Control Plant

Specialist contractors were brought in early to the project as it was identified that the nature of the project needed their specific expertise in the planning stages as well as the

Figure 6. Tell Tails on the top of the cliff

construction itself. One contractor had two excavators available that had been modified to enable remote control. These were very valuable in terms of managing health and safety on the project. With the remote control capability, we were able to define no-go areas within the site for manned machinery. The position of the no-go line was first determined based on the rockfall modelling, during construction, the modelling was updated, and the no-go line adjusted accordingly, refer to Figure 7. The “Fly-Model-Analyse” process was developed where the drone flight was undertaken at the start of each week, the photogrammetric model produced and from this cross sections were taken that were then fed into the rockfall modelling software and within 48 hours of flying the site, the new no-go line was confirmed.

All the machinery on site had the 3D design models loaded into the machines and as such the no-go line could be updated each week and this was loaded into the diggers so that the operators knew they were always working from the latest data rather than relying on paper plans that may not have been superseded.

Figure 7. 2D rockfall models incorporated with the 3D photogrammetric model

5.1.5 Hold Points

The whole project encompassed many different phases of work, from moving the material debris already at the foot of the cliff, the demolition of the buildings, retaining walls and clearing vegetation, to the temporary haul road, excavating the rock and placement for the mass earthworks. The project was managed via hold points. Specific meetings were held prior to commencing the next major phase or significantly new task. The team adopted this approach throughout all the demolitions in the Port Hills as the situations could change quickly; every property demolition we undertook ended up deviating from the original plan in some way. Hold points were a very good way of reminding the workers (and any new personnel) of the hazards and risks. It was easy for the teams to get a little blasé throughout the project, as we were fortunate enough to have no significant aftershocks, no significant rain events and no failures of loose material from of the cliff.

5.1.6 Virtual Reality site inductions

With the use of the drone and the creation of the photogrammetry 3D models, we conducted the site inductions off-site using augmented and virtual reality, refer to Figure 8. The health and safety and productivity advantages of being able to make people familiar with the site prior to entering were significant, particularly when it was a small site with the usual construction site related hazards but with the addition that the entire site was at risk of some rockfall. The site offices provided a level of protection, but if there had been a significant earthquake,

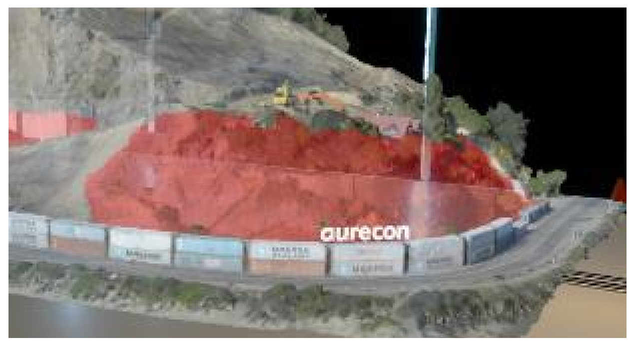

Figure 8. 3D model of the site as viewed through the HoloLens that we used for site inductions

personnel on site needed to be able to react quickly.

6 DISCUSSION

Engineering is a noble endeavour when applied to enriching our lives. In this case study the geotechnical engineering effort before, during and after the earthquake sequence was massive and had significant positive impact in getting our community ‘back to normal’. Great engineering intersects seamlessly with the community it serves and in our case, we needed engineering to work harder, faster, longer and in a more complex environment than we had ever seen. Engineering of this sort directly affects lives families and livelihoods, this overlap of engineering rationale and ‘real-life’ impacts served a very good reminder to the engineering community that they needed to understand the intangible impacts of their decisions, as well as the tangible.

We also needed the engineering works to be safe, the earthquake had already directly caused 186 fatalities – it was our stated intention from as soon as the response began – that our work program to restore the city was not going to cause that number to rise. The engineering community had to build and maintain trust that their advice was proportional to the risk, had recommendations that would withstand scrutiny in court, in Parliament and in the wider community. We are pleased to say that to date, our engineering program in Christchurch has had no links to any workplace fatalities *and long may that continue.*

In order to give effect to the engineering opportunities, we needed bold public policy and the land zoning around the city delivered that. We needed time and room to gather and analyse the data required to make sound, long-term engineering decisions. Land zoning is contentious and inexact due to the very nature of the area it covers. Holistically it provides certainty and a way out of a dire situation that many thousands of people would have found themselves in – with little or no hope of recovering any value from their property.

Any public sector executive, when faced with massive spending requirements will always ask ‘where is the money coming from?’ In New Zealand’s case, this could be answered in three parts.

- Firstly - the NZ Government displayed leadership and commitment to the region by establishing a recovery agency and underwriting a series of major rebuild anchor projects, this provided investor and community confidence.
- Secondly – NZ is heavily insured as a nation. While some of the issues the earthquake created are big, complex and distressing, we have insurance money available to ease the burden. It is a far from perfect model, but much better than having no money.
- Lastly – NZ is one of very few countries that insures land, this is done through the Earthquake Commission. Money raised through land ownership and insurance policies, this is used to pay premiums to off shore re-insurers, and Insurance monies are made available to help property owners recover from events such as this.

7 APPLYING WHAT HAS BEEN LEARNT

As the authors were writing this paper, New Zealand experienced a second major earthquake series. At 00:02 on 14th November 2016, a M7.8 earthquake struck north Canterbury near Kaikoura. The earthquake caused extensive landslip damage blocking the main transport route north-south down the south island in such a way that Kaikoura was inaccessible by road for several days and it has taken several weeks to enable public road access. This was due to the severity and magnitude of the hundreds of landslides in the region. Kaikoura is a small town where Christchurch was a large city but the two events are similar. The emergency response stage has been very complicated with the Kaikoura event due to the very large expanse of the country affected and so there have been three main control centres coordinating the response. The area has crossed regional council boundaries and has involved the local, regional and national parts of the Civil Defence organization to coordinate closely.

Many of the lessons learned throughout the Christchurch earthquake have been built upon and once again, the engineering community has come together forming a quick and coordinated response. The template used for the Christchurch infrastructure rebuild alliance is being adopted in order to reopen the state highway network. Kaikoura relies heavily on the tourist trade and without reliable roads to the town, the tourists will not visit.

New Zealand now has a specific Earthquake Ministerial position in Parliament and this has been an integral part to managing the earthquake response.

8 CONCLUSION

The Christchurch earthquakes were unprecedented and very much unexpected. The fault line was not known about and it serves to remind us that assuming there are no risks can be flawed thinking. The “expected” fault line was the earthquake that occurred in November 2016 at Kaikoura and although the shaking in Christchurch lasted 2min 20 seconds, no significant damage was sustained due to the low peak ground acceleration. The New Zealand Building code has saved many lives as the earthquake was more than double the ultimate limit design, yet very few buildings collapsed. The rockfall that occurred had not been seen on this scale and a huge amount of experience has been gained by those working on the recover and rebuild work. Resilient design is a situation that should be aimed for, however, it comes at a cost. The design PGA in Christchurch was 0.3-0.5. The 2011 earthquakes showed a maximum of >2G. If engineering projects are to be truly “resilient”, then what PGA is appropriate?, more resilience comes at a greater cost, but is that greater cost worth it if the earthquake turns out to be 4 times larger than expected? We have to take a risk-based approach and ensure that our clients really understand the implications and potential consequences.

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