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Rebuilding with Resilience: The Story of the Fire Station Rebuilds in Christchurch

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ABSTRACT

Following the Canterbury Earthquake Sequence (CES) between 2010 and 2011, a number of the fire stations in the Canterbury area were severely damaged. The key aspect for the fire stations rebuild design was the philosophy of rebuilding with resilience, where the geotechnical design was not only governed by site performance during an ultimate limit state seismic event but also the ability for the fire station buildings and ancillary infrastructure to be repaired, if required. The philosophy provided a practical balance between the costs associated with ground improvement, the performance of the fire station facility during seismic events, its post disaster functionality and ability to be repaired.

The first stage in determining the level of resilience required extensive geotechnical input, including back analysis of the site performance during the CES to improve the assessment for the predictive models of future design events. Based on the geotechnical risks at the specific sites, a tiered approach to the level of resilience design and detailing was used with extensive detailing for high geotechnical risk sites, cascading down to a lower level of detailing for low geotechnical risk sites.

This paper presents five case studies for rebuilding fire stations on ground susceptible to seismically triggered liquefaction. The geotechnical mitigation solutions ranged from deep ground improvement to geogrid reinforced gravel rafts. The additional resilience design features associated with the enhanced foundations and horizontal infrastructure detailing are discussed, to demonstrate the approaches taken to manage geotechnical risks associated with post disaster functionality for high importance structures.

1 INTRODUCTION

Fire and Emergency New Zealand (FENZ) is the unified organisation that provides emergency response services for New Zealand, including firefighting. Following the Canterbury Earthquake Sequence (CES) from 2010 to 2011 a number of Canterbury region's fire stations were severely damaged, due to shaking damage to the structure combined with the effects of widespread liquefaction induced ground damage. The level of damage required multiple fire station rebuilds. In addition, the post-earthquake environment provided a unique opportunity to reassess the configuration of the fire station network.

Although a large number of businesses and residents relocated to parts of the city where ground conditions are less challenging due to post-earthquake land zonings, fires stations need to be in optimised locations to be able to respond to emergencies and service their community. Hence, fire station sites will need to be situated in areas where geotechnical hazards such as potentially liquefiable ground are present.

To date a total of twelve fire stations have or are in the process of being rebuilt within the city and the surrounding region. Of these, five are discussed in this paper which include, ANZAC Fire Station, Spencerville Fire Station, Redwood Fire Station, Woolston Fire Station and Central City Fire Station.

2 RESILIENCE CRITERIA

In the New Zealand Building Code a building is given an importance level (1-5) determined by risk to human life, the environment, economic cost and other risk factors in relation to its use. Due to their post disaster functionality requirements, fire stations are categorised as an Importance Level 4 (IL4). FENZ has taken this further by ensuring the runout apron from the fire station to the road performs to a similar level as the buildings, to ensure access from and to the station is maintained.

IL4 structures such as fire stations are designed for three earthquake design cases which include Serviceability Limit State 1 (SLS1), Serviceability Limit State 2 (SLS2) and Ultimate Limit State (ULS). The level of shaking for each case are currently defined by two documents, which include the NZS1170 *Structural Design Actions* and NZGS/MBIE *Earthquake geotechnical engineering practice, Module 1: Overview of the guidelines*. The following table summarises the seismic design parameters for an IL4 structure.

Table 1: Importance Level 4 earthquake loading design cases in Canterbury, NZ

Method	Design Earthquake*	Return Period*	Magnitude	PGA
NZGS/MBIE	SLS1	25 year	6.3	0.09g
NZGS/MBIE	SLS2	500 year	6.2	0.27g
NZGS/MBIE	ULS	2500 year	6.2	0.48g
NZS1170	SLS1	25 year	7.5	0.11g
NZS1170	SLS2	500 year	7.5	0.35g
NZS1170	ULS	2500 year	7.5	0.61g

*Design events and associated return periods derived from NZS1170.0.

For IL4 structures, the liquefication analysis used this range of earthquake design parameters to give a broad understanding of the likely effects of liquefaction for the various iterations of magnitude and peak ground acceleration (PGA) that may affect the site.

Although the Christchurch area has a heightened level of seismicity, higher earthquake design cases such as Maximum Credible Events were not considered necessary to evaluate. Soils typically liquefy at approximately SLS2 level of shaking and increases in the magnitude or PGA do not necessarily result in proportionally higher levels of liquefaction induced settlements or damage.

3 LOCATIONS

The five fire station rebuilds discussed in this paper are located over the wider geographical area of the city, with contrasting ground conditions. The fires station locations are shown in Figure 1. Of these five stations, two were rebuilds on existing sites (Central City and Woolston) and the remainder were new sites. Although the majority of the sites are near the Christchurch metropolitan area, the sites experienced differing levels of peak ground acceleration during the CES, resulting in different levels of observed damage. A summary of the operational requirements of the station, underlying ground conditions and level of ground damage experienced during the CES is presented in Tables 2 and 3.

Figure 1: Fire station locations

Of the five fire station sites, all were underlain by ground conditions that had liquefied during the CES and caused ground damage, or could potentially liquefy but did not experience sufficient levels of shaking to induce liquefaction ground damage. It is considered somewhat fortuitous that a number of the sites experienced reasonably high levels of ground shaking, so there was an initial understanding of the extent of ground damage in future seismic events.

The structural form of the new fire station buildings is typically light weight, with light weight exterior cladding and roofing, although the buildings are typically 4m to 5m high.

Table 2. Fire station operational requirements and ground conditions.

Station	Operational Requirements	Ground Conditions
ANZAC	4× Bay Composite Station (Career and Volunteer)	Interbedded loose sand and stiff silts to 4m underlain by loose to medium dense sands to at least 20m. Groundwater typically at 2m depth.
Spencerville	2× Bay Volunteer Station	Interbedded loose to dense sand and firm to stiff silt to at least 20m. Groundwater typically at 1m to 1.5m depth.

Station	Operational Requirements	Ground Conditions
Redwood	2× Bay Career Station	Interbedded loose to medium sand and firm to stiff silts to 5m, underlain by dense sand and gravel to 11m, then firm to stiff silts to 15m and dense gravel to at least 20m depth. Groundwater typically at 2m depth.
Woolston	2× Bay Career Station	Interbedded loose sand and stiff silts to 2.5m, underlain by loose to medium dense sands to at least 18m. Groundwater typically at 1m to 1.5m depth.
Central City	4× Bay Career Station	Interbedded loose sand and stiff silts to 4m, underlain by dense gravel to 9m on western side of site. Dense gravel from shallow depths to 9m on the eastern side. Dense sand and firm silt to at least 15m depth. Groundwater typically at 2m to 2.5m depth.

Table 3: Level of ground damage experienced at fire station sites.

Station	Level of Seismic Shaking Experienced	Level of Ground Damage
ANZAC	Between SLS1 and SLS2	Minor observed ground damage but no lateral spreading (Avon River over 100m away from site).
Spencerville	SLS1	Minor ground damage observed on site with no lateral spreading (Styx River approximately 80m away from site).
Redwood	SLS1	No observed liquefaction induced ground damage.
Woolston	SLS2 and greater	Moderate to severe ground damage with extensive sand boils on site and lateral spreading towards the Heathcote River which is 40m away.
Central City	Between SLS1 and SLS2	Moderate ground damage on western side of site. Notably the western side of the old station building tilted to the west.

4 LIQUEFACTION HAZARD

A liquefaction hazard assessment was carried out using cone penetrometer test (CPT) information obtained for each site and the liquefaction analysis methods detailed in the Ministry Business, Innovation and Employment (MBIE) Guidelines (2012), which were based on Boulanger and Idriss (2014) method. In addition, the likely level of liquefaction induced ground damage was assessed using the Liquefaction Severity Number (LSN) method developed by Tonkin & Taylor (2013).

As part of the assessment, back analysis of the site performance during the CES was undertaken to improve the assessment for the predictive models of future design events. This included calibration of liquefaction models with the actual observed ground damage and measured settlements. From the liquefaction assessment the likely level of liquefaction induced settlement and ground damage at the different fire station sites in future seismic events are summarised in Table 4.

Table 4: Level of index settlement and ground damage at fire station sites

Station	SLS1		SLS2		ULS	
	Settlement*	Damage**	Settlement*	Damage**	Settlement*	Damage**
ANZAC	<30mm	None	95 to 115mm	Moderate	105mm to 135mm	Moderate to Major
Spencerville	<20mm	None to Minor	70 to 95mm	Moderate to Major	85mm to 110mm	Moderate to Major
Redwood	<15mm	None	60 to 95mm	Moderate	75mm to 100mm	Moderate
Woolston	<30mm	None	40 to 170mm	Moderate to Major	50mm to 175mm	Moderate to Major
Central City	<5mm	None	5 to 90mm	Minor	5 to 95mm	Minor to Moderate

* Indexed settlements are calculated over the upper 10m CPT profile

** Damage is based on calculated LSN number

In addition, the Woolston Fire Station site had a moderate to major lateral spreading hazard, while the lateral spreading potential was assessed as not significant for the ANZAC, Spencerville and Central City Fire Stations.

5 ENGINEERING SOLUTIONS

The key aspect for developing engineering solutions for the fire stations design was the philosophy of rebuilding with resilience, where the geotechnical design was not only governed by site performance during a seismic event but also the ability for the fire station buildings and ancillary infrastructure to be functional post disaster and being able to be readily repaired, particularly after a SLS2 event. The philosophy provided a practical balance between the costs associated with ground improvement, the performance of the fire station facility during seismic events, its post disaster functionality and ability to be repaired. This was of importance as the majority of the fire stations within the Christchurch City metropolitan area had to be rebuilt.

The philosophy required a multidisciplinary approach to build in resiliency through soil-structure-interaction (SSI), a combination of ground improvement, enhanced foundation systems and service detailing. Aspects the designers considered when defining the geotechnical solutions included the nature of the building structure, the majority of the fire station structures are typically single-storey well braced structures made of lightweight materials. Being relatively light weight structures allowed the use of enhanced shallow foundations that can be designed to cantilever if there was loss of support. The rigidity of the foundation system allows for relevelling if there are differential settlements. In addition, for the Redwood and Spencerville Fire Station site, general site development required a build-up of 1m to 1.5m of bulk fill to bring the site levels above flood levels. Placement of bulk fill was accounted for in the designs to increase the non-liquefiable crust at the site and therefore provide improved site performance.

The engineered solutions for the development on the fire station sites are presented in Table 5.

Table 5: Engineering solutions for the fire station sites.

Station	Engineering Solution	Comments
ANZAC	Deep ground improvement with Rammed Aggregate Piers (RAP)	Ground improvement considered necessary as a large station critical to the eastern Christchurch community was to be placed on the site, and the site has experienced ground damage during the CES with the potential for high levels of ground damage and settlement at ULS levels of shaking. 600mm diameter RAPs were installed to 7m depth at 2.0m centres for 8% area replacement ratio, to provide a thick non-liquefiable crust that greatly reduced liquefaction induced settlement and ground damage at the surface. The foundation comprised of well tied together concrete ground beams connected to a concrete slab. Due to low expected differential settlement there was no need for any specific service or horizontal infrastructure detailing.
Spencerville	Geogrid reinforced gravel raft with the fire station building on a well reinforced concrete raft foundation	Potential for moderate to major ground damage and high levels of settlement. On site bulk filling was required to bring levels approximately 1.5m above existing ground level. Therefore, a combined reinforced gravel raft and robust foundation system was used. The gravel raft was typically 1.8m thick, extending 2m out from the building footprint, with three layers of Naue Secugrid 40/40 Q1 geogrid placed in well compacted, angular well graded AP40 gravel. Foundation elements were well reinforced (enhanced) concrete raft and with services detailed to be wholly enclosed in the raft.
Woolston	Deep ground improvement with stone columns	Ground improvement considered necessary as the site has performed poorly during CES, with the potential for high levels of ground damage and differential settlement, as well as, lateral spreading hazard being present. Stone columns considered the most appropriate method due to predominantly sandy soils. 780 No. 600mm diameter stone columns were installed to 9m depth at 1.65m centres for 12% area replacement ratio, to provide a thick non-liquefiable crust that significantly reduced liquefaction induced settlement and ground damage at the surface. Foundation elements require a well reinforced (enhanced) concrete raft. As the ground was no longer susceptible to ground damage there was no need for any specific service detailing.

Station	Engineering Solution	Comments
Redwood	Geogrid reinforced gravel raft with the fire station building on well reinforced concrete ground beams and slab foundation	Ground damage typically moderate with less than 100mm settlement. In addition, on site bulk earthworks required to bring levels approximately 1m above existing ground level, which allowed the use of a reinforced gravel raft. Gravel raft 1.5m thick with similar detail to Spencerville Fire Station. Foundation elements require concrete beams and slab with services enclosed within the ground beams.
Central City	Geogrid reinforced gravel raft with the fire station building on a well reinforced concrete raft foundation for western part of building. Seismic break in the structure with the eastern part of the building on hardfill pad with shallow foundations.	Potential for minor/moderate ground damage and moderate levels of settlement on western side of site. On eastern side no ground damage and minimal settlement due to presence of shallow gravels. Therefore, the station has been separated into two structures with a seismic break in between and different foundation requirements under each part of the building. Gravel raft typically 1.5m thick with similar detailing to Spencerville Fire Station. Foundation elements require well tied together reinforced (enhanced) concrete raft and services detailed to be structurally enclosed in the raft foundation.

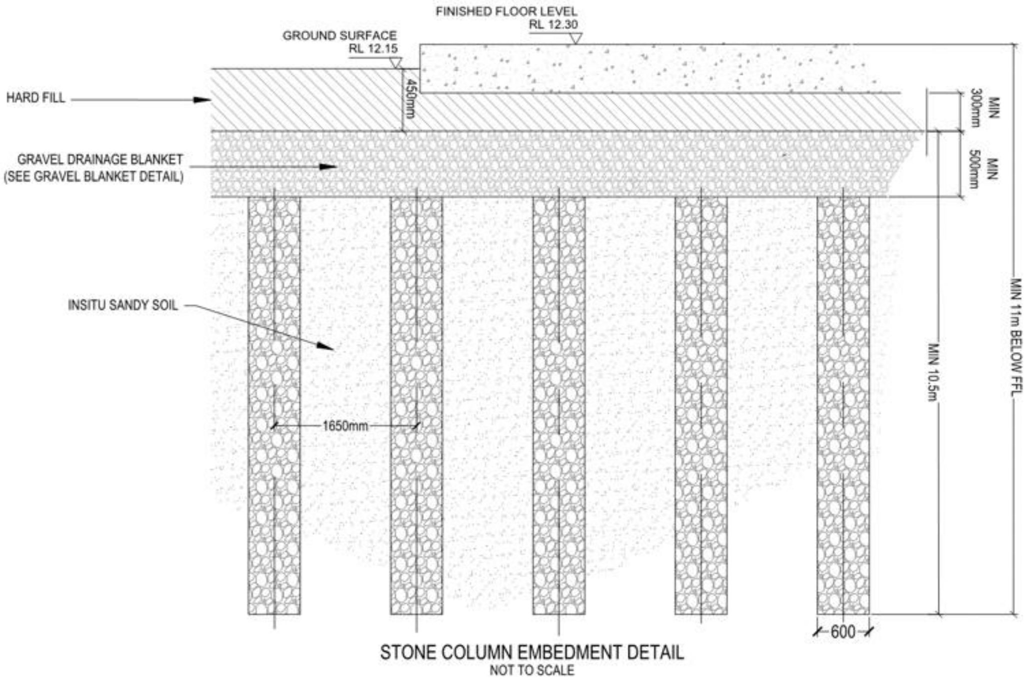

Figure 2: Typical stone column detail at the Woolston Fire Station site.

For the ANZAC and Woolston Fire Stations the geotechnical hazards associated with the building sites were eliminated by carrying out deep ground improvement to form a thick non-liquefiable crust under the building. Typical details of the stone column construction at the Woolston site are presented in Figure 2.

A reinforced gravel raft with the building constructed on a well reinforced (enhanced) concrete raft foundation was considered an economical and practical solution, where the station structure was to be a smaller two bay station or where the level of liquefaction induced ground damage was not as severe. Although in a large seismic event liquefaction induced settlement and ground damage may occur the building foundations will perform to an appropriate standard as:

- Field based trials in Christchurch of densified crusts have shown that shaking induced settlements are reduced by over half, which will reduce total and differential settlements across the structure.
- Settlement due to ratcheting and bearing capacity failure of individual building foundations are unlikely to occur through the gravel raft, provided the building foundations are appropriately designed to distribute building loads.
- Hogging potential of the foundations due to differential settlement following a strong earthquake is unlikely as the reinforced gravel raft and the enhanced foundation system provide a stiff system.
- Voids under the gravel raft due to soil evacuation from liquefaction induced sand boiling are unlikely to occur as the gravel raft extends out 2m from the footprint, and hence the travel path of the liquefied soil is extended.
- Some differential tilting may occur over the structure during larger earthquake events, but this is unlikely to adversely affect the building function and an enhanced foundation system can be readily re-levelled off the reinforced gravel raft, if required.
- The reinforced gravel raft and building plan layouts were kept as regular as possible to allow better structural performance and distribution of stresses on the foundation.
- The Spencerville and Redwood Fire Stations, where bulk earthworks were required to lift the land above existing ground conditions, a thicker non-liquefiable crust was created. This significantly reduced the liquefaction induced ground damage potential.

Based on the above performance criteria the geogrid reinforced gravel raft provides a high level of resilience to maintain post disaster functionality. An added feature is the ability to be repaired. Typical details of reinforced gravel raft are present in Figure 3.

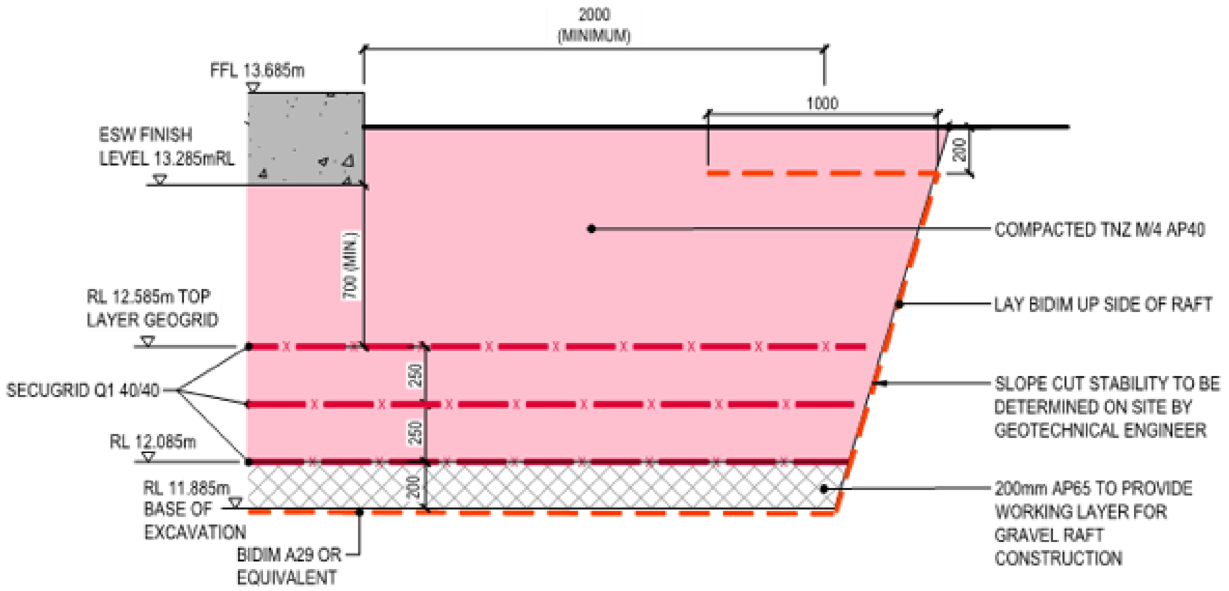

Figure 3: Typical reinforced gravel raft detail at the Redwood Fire Station site.

Collaboration between geotechnical and structural engineers created well reinforced and tied together concrete raft foundations, 300mm to 400mm thick, which provide robust foundations that distribute load and minimise differential settlements.

A critical aspect of improving the building performance and functionality after a large earthquake is detailing services (water, stormwater, wastewater, power and telco) for the building. If underground and under-slab service are damaged even in a moderate sized earthquake due to differential settlement across the structure then the functionality of the building is reduced, and repair may be difficult, costly or not possible. Where deep ground improvement has been carried out, such as at ANZAC and Woolston Fire Stations, then the need for service detailing was not as rigorous. But in the remaining sites where a certain amount of settlement and ground damage may occur following a large earthquake, service detailing included:

- All pipes and conduits under the concrete raft slabs were encased within, or structurally connected to the underside of the concrete floor slab. All services were contained within the concrete foundations and service penetration into the underlying geogrid reinforced gravel layer were not permitted.
- Pipes and service conduits were made from flexible material where practicable. End restraints and slip collars were utilised in pipe joints and intersections with manhole risers.
- Attention was given to detailing the connections of buried services (water and sewer pipes, power conduits, etc.) between the building foundation, the engineered gravel raft/ground improvement and in situ ground. The design allowed for sufficient movement and ductility to account for seismic shaking and liquefaction induced movement, and to allow for reinstatement in the event of damage.

6 CONCLUSIONS

The case studies presented are for five fire stations located on liquefiable ground. The seismically induced liquefaction hazard and operational requirements by FENZ governed the foundation design. The fire station buildings are of high importance (IL4) with post disaster functionality. They are typically made with lightweight materials and are well braced. Resilience was built in through a collaborative cross disciplinary design approach providing ground improvement with enhanced foundation systems and low damage service detailing. The geotechnical solutions included ground improvement with stone columns and RAPs, and geogrid reinforced gravel rafts. In addition to the geotechnical solution, resilience design features included structurally enhanced well tied together foundations and service detailing, which demonstrates a practical approach to manage geotechnical risks associated with high important structures.

7 REFERENCES

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