Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Building Post-Earthquake Business Resilience Through Geotechnical Design: A Christchurch Case Study

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ABSTRACT: Following the major earthquake events of 2010 and 2011 in the Canterbury region of New Zealand, Foodstuffs South Island Ltd has rebuilt four of their earthquake damaged supermarket buildings. The earthquake losses resulted in significant economic loss and business disruption from both the physical loss and during the rebuild process. All four supermarket buildings were damaged beyond practicable repair primarily by the effects of seismically induced liquefaction at levels of shaking below that of a code life safety event.

As part of the rebuild process a key driver for Foodstuffs has been to build post-earthquake resilience into their new buildings. From a business perspective this practicably means that following a major earthquake Foodstuffs accept some minor property damage and disruption to trade may occur but they want to minimise the likelihood of extensive repairs to, or rebuilding of, their stores.

From a geotechnical engineering perspective this business resilience has been primarily achieved through the mitigation of the liquefaction hazard present at Foodstuffs sites and using design details that maximise ease of reparability following a major earthquake event. This approach has often resulted in geotechnical designs that exceed the minimum Building Code requirements and utilised the latest research and technology available where possible.

This paper outlines, by way of case studies, the key geotechnical drivers adopted by Foodstuffs to mitigate against the liquefaction hazard at four of their rebuild sites and to maximise their post-earthquake business resilience.

1 INTRODUCTION

Following the major earthquake events of 2010 and 2011 in the Canterbury region of New Zealand, Foodstuffs had to rebuild four of their earthquake damaged supermarket buildings. All four supermarket buildings were damaged beyond repair primarily by the effects of seismically induced liquefaction. These losses have resulted in significant economic loss and business disruption from both the physical loss and during the rebuild process.

A key driver for Foodstuffs as part of this rebuild process, and subsequently adopted for new builds, has been to build post-earthquake resilience into their new buildings. From a business perspective this means that following a major earthquake Foodstuffs accept some property damage and possible disruption to trade may occur but they want to minimise the likelihood of requiring extensive repairs to, or rebuilding of, their stores.

Due to the disproportional damage caused by liquefaction when compared to ground shaking only, from a geotechnical engineering perspective this business resilience has been primarily achieved through the mitigation of the liquefaction hazard. It has included using design details that maximise ease of reparability following a major earthquake event and often resulted in geotechnical designs that go well beyond the minimum Building Code requirements.

2 LOCAL GROCERY INDUSTRY

The New Zealand Supermarket Industry is highly competitive with two main players; namely the two Foodstuffs Cooperatives of North Island and South Island and the Woolworths Australia operation. Foodstuffs South Island operates solely in the South Island of New Zealand and along with its counterpart in the North Island, commands approximately 60% market share of their respective regions.

Foodstuffs provides the infrastructure and support network behind the Owner/Operator Cooperative with the main supermarket brands New World and PAK'nSAVE providing the public front. Foodstuffs is predominantly the owner of the sites and buildings that the Owner/Operators trade out of. These stores are strategically positioned based on population size, location of neighbourhood shopping districts and malls, and key arterial routes.

Local communities rely on the existence of the supermarket as do the local businesses, and the continuation of trade is vital for the Owner/Operators, given the highly competitive nature of the industry. The supermarkets are also large employers of unskilled, semi-skilled and part-time labour and are vital to the economic and social well-being of the communities they serve. These elements subsequently offer no real flexibility in moving or closing a business post-earthquake, while repairs or rebuilding is completed.

Combined with Foodstuffs central distribution network, the ongoing operations of the logistics supply chain and supermarket operations is critical for the business viability of the Owner/Operators and the overall Cooperative.

3 TYPICAL BUILDING STOCK

At the time of the earthquakes Foodstuffs' supermarket building stock within the Christchurch region were typically built in the 1970's through to early 2000's.

Supermarket buildings typically comprise a 3,000m^2 up to 6,500m^2 floor plates, with large single storey open plan market floor area. They contain a back of house area that typically contains delicatessen, bakery, butchery, chiller/freezers and bulk store areas which comprise approximately one-third of the building footprint. There is also typically a small area of mezzanine floor with office and administration spaces. Both the back of house and market floor areas have extensive underfloor services associated with plant and equipment required for the day to day operation of the stores.

Structurally the modern buildings are not dissimilar to a large modern warehouse type buildings, with a reasonably light weight structure, including large span steel portal frames and glass and tilt slab concrete panel cladding and light weight roofing.

The buildings range from free standing at their own location with, or without, small scale attached retail shops, or part of extensive urban shopping mall complexes.

The vast majority of the pre-earthquake Christchurch supermarket buildings were founded on simple shallow pad and strip foundation systems with lightweight floor slabs which were often floating and not always connected to the foundations. However, some of the buildings were founded on piles or extra wide strip footings with integral floor slabs spanning between supports acting much like a raft foundation.

4 GEOLOGICAL SETTING

Christchurch is New Zealand's second largest city with a population of approximately 500,000 in the city and the immediate region. It is located on the coastal margin of the Canterbury Plains on the east coast of the South Island of New Zealand.

The upper soils are typically Holocene deposits. The soils under the eastern part of the city are often much less than 6,500 years old and waterlogged. Soils typically comprise interbedded layers of silts and sands with gravel outwash material from the Canterbury Plains and the Southern Alps to the west. Towards east/coast the outwash materials are interbedded with estuarine, swamp and dune deposits. The southern edge of the city is bounded by the Port Hills which are formed by a now extinct Lyttelton

Volcano system (Brown and Weeber, 1992).

The outwash gravel beds typically dip towards the coast with the overlying soils being less than 5m thick in the west and over 40m depth towards the coast.

Groundwater is reasonably deep on the western side of the city but is getting closer to ground surface towards the eastern suburbs and the coast. Typical ground water depths are less than 1m or so in the eastern suburbs and up to 6m in the western suburbs (van Ballegooy et. al., 2014).

5 CANTERBURY EARTHQUAKES AND DAMAGE

The Canterbury earthquake sequence commenced on 4 September 2010 with the M_w7.1 Darfield Earthquake and to date included over 13,000 felt aftershocks. The largest of these aftershocks was the 22 February 2011 M_w6.2 Christchurch Earthquake (GNS, 2015).

The Darfield and Christchurch Earthquakes resulted in widespread land and building damage in Christchurch, including the loss of 185 lives after the February 2011 event. This damage included significant seismically induced liquefaction in the east and southwest areas of the city.

From Foodstuffs perspective these major earthquakes caused varying damage to their building stock throughout the city.

At sites with favourable conditions the earthquake damage typically manifested itself as forms of structural damage with little or no foundations movement. These sites were typically functioning in the order of hours to days following the earthquakes and overall the buildings performed well from a seismic perspective. These sites typically had:

- the ground was better (typically on the western side of the Christchurch region with shallow gravel layers and deeper water table); and/or
- where the ground shaking was of a lower intensity; and/or
- specific regard had been taken for seismically induced liquefaction during the building design.

For sites where unfavourable conditions prevailed significant building damage occurred with a major portion of structural damage being attributed to the effects of liquefaction with shallow bearing failures and excessive settlements. These sites either required major repairs and building re-levelling, or building rebuild. Typically building rebuilds were taking a minimum of 15 months with associated business and social disruption. These sites were typically where:

- the ground was poorer (typically on the eastern side of the Christchurch region) with loose saturated silty-sandy soils with high water table; and/or
- there were high ground accelerations; and/or
- no regard was given to the effects of liquefaction during the original building designs.

The location of the various supermarket sites and damage levels are shown in Figure 1 below. The damage resulted in the complete rebuild of four supermarket buildings and major repairs and revelling to one.

The approximate earthquake loading, equivalent return period for rebuild and major repair sited from the New Zealand design loadings standard (NZS1170.5:2004) and the foundation failure modes are described in Table 1 below. All five buildings were supported on shallow foundation systems of various forms and were not specifically designed for the effects of seismically induced liquefaction. All sites suffered extensive ground damage and are in areas that have been subsequently zoned with the highest liquefaction risk in the Government lead post-earthquake land zoning exercise. With the exception of the Kaiapoi site, where the foundation damage was mainly caused by lateral spread and stretch, with over 300mm of stretch in the floor of the building and over 1m across the site, the majority of the damage was caused by punching failures of the shallow footings through thin non-liquefied crusts into the underlying liquefied silty-sandy material. Which resulted in significant differential settlement and associated structural and service damage. This was more pronounced at St Martins and Redcliffs sites where the crust was less than 1m thick and the ground shaking significantly higher, approaching the revised 500 year return period Ultimate Limit State / Life Safety level earthquake event, than the

Wainoni site where the crust is 1.5m to 2m thick and the earthquake shaking intensity was lower, calculated to be a 300 year return period event. The Stanmore Road store was founded on a uniform grid of pad and strip footings all well tied together with ground beams and an integral floor slab founded on a 3 to 4m thick non-liquefied crust of soft to firm clayey-silty material interbedded with sand. This particular building suffered large differential settlements but was in the end successfully repaired and re-levelled with resin and grout injection. The Wainoni, Kaiapoi and Stanmore Road sites all experienced significant damage at levels of geotechnical induced damage at levels of ground shaking in excess of the 1 in 25 year Serviceability Limit State / no-damage earthquake event, but except for the St Martins site, less than the 1 in 500 year Ultimate Limit State / Life Safety level event.

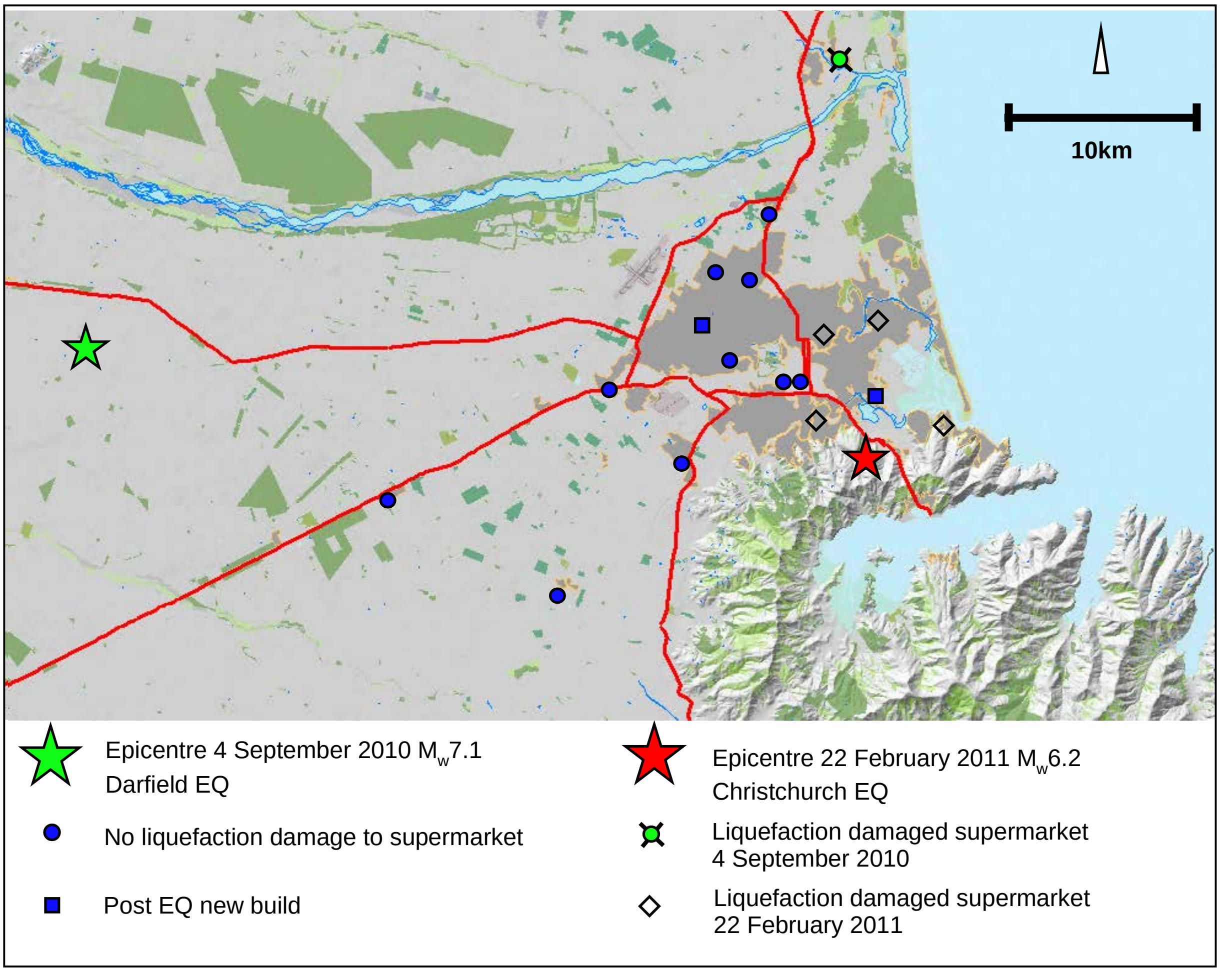

Figure 1 – Earthquake epicentres and supermarket locations

Table 1. Summary of the site failures

Site	EQ	M_w	PGA_{50}*	$PGA_{M_w}7.5$ Equivalent	NZS1170.5 Return Period	Non-Liquefied Curst Thickness
Kaiapoi	Darfield	7.1	0.23g	0.20g	150yr	2.5-3m
St Martins	Christchurch	6.2	0.56g	0.35g	550yr	<1m
Redcliffs**	Christchurch	6.2	0.59g	0.37g	400yr	<1m
Wainoni	Christchurch	6.2	0.44g	0.27g	300yr	1.5-2m
Stanmore Rd	Christchurch	6.2	0.44g	0.27g	300yr	3m

*Canterbury Geotechnical Database (2015)

** Shallow Soil - Class C site - hence higher design earthquake loads from the New Zealand loading standard than the other Deep Soil - Class D sites

Throughout the earthquake sequence several other of Foodstuffs' stores experienced significant ground shaking, in particular in the southwest during the Darfield Earthquake. This shaking resulted in no geotechnical induced damage which is attributed to the fact that the ground conditions under these stores were favourable with competent gravel soils present at shallow depths and deep water table. The noticeable exception is the Halswell store dating from the early 2000's which is founded on a quasi-raft type foundation system. This site suffered moderate liquefaction and ground damage during the Darfield Earthquake. However, the store suffered no geotechnical induced damage, while the neighbouring shops founded on isolated shallow footings did suffer reasonably significant liquefaction induced foundation and building damage. This differing response between a well tied raft and isolated shallow foundations well illustrates the benefits of liquefaction mitigation in building design.

From Foodstuffs and the wider communities' perspective, the earthquake damage and the loss of four supermarkets created long lasting impacts, not just for the Cooperative, but in the respective communities themselves. The largest impact could be felt with the loss of employment. Across the St Martins, Redcliffs and Kaiapoi supermarkets, well over 200 full-time employees were made redundant, along with a considerable number of part-time employees. Many of those made redundant had also suffered loss in the earthquakes in their private lives and along with the closure of the supermarket, compounding the loss to these communities.

Aside from the physical loss of the supermarket properties themselves, the biggest impact is the loss of trade over the medium to long term. During the rebuilding stage the public were forced into different shopping patterns and whilst this had an immediate disruption to their lives, many of them were displaced themselves due to the earthquake and to retrieve those lost sales proved challenging once trading recommenced. Although Kaiapoi and St Martins were rebuilt relatively quickly, 15 months and 19 months respectively, the heart of their communities had been severely impacted, not just with the loss of jobs, but the sense of a community structure had been severely dented and this took considerable time to repair.

6 KEY REBUILD DRIVERS AND BUSINESS BENIFITS

In general terms the New Zealand Building code has two thresholds for earthquake induced damage, the Serviceability Limit State (SLS) event where no structural damage is expected, with no real loss of amenity and only nominal repair required, and the Ultimate Limit State (ULS) event which is primarily concerned with life safety. Structural damage is expected in the ULS case but no collapse or catastrophic failure is expected and ideally the damage is repairable. Using the New Zealand structural code (NZS1170.5:2004) there is effectively a linear increase in structural demand, and expected damage, between the two limiting states.

Liquefaction on the other hand has typical binary response with increasing seismic demand, i.e. non-liquefied tripping out to full liquefaction effects over a relatively small increase in ground acceleration or number of shaking cycles. Once liquefaction is triggered there will be minimal increase in ground damage even with a significant increase in ground acceleration.

Using reconsolidation settlement provides a qualitative method to demonstrate the binary nature of liquefaction response as shown in Figure 2 for Foodstuffs' St Martin site.

Figure 2 demonstrates that onset of liquefaction occurs just before the nominal Serviceability level earthquake (0.13g & M_w7.5 - 25 year event), while approximately 90% of ULS earthquake (0.35g & M_w7.5 – 500 year event) settlement/damage has occurred at say 0.20g & M_w7.5 (150 year) event. Therefore from a geotechnical perspective, ULS level ground damage is occurring long before a ULS event has occurred. Thus an expected linear increase in structural damage, with a linear increase in ground shaking will not occur at sites susceptible to seismically induced liquefaction.

Therefore, without specific regard to liquefaction and its effects in design, significant levels of ground and associated structural damage can be expected to occur at only moderate levels of ground shaking.

The key reason for the total building losses at Kaiapoi, St Martins, Redcliffs and Wainoni was due to geotechnical/liquefaction effects at these sites. The onset of liquefaction induced ground damage is expected at around, or before, the SLS event with significant liquefaction induced ground damage expected at levels of shaking significantly less than a ULS event.

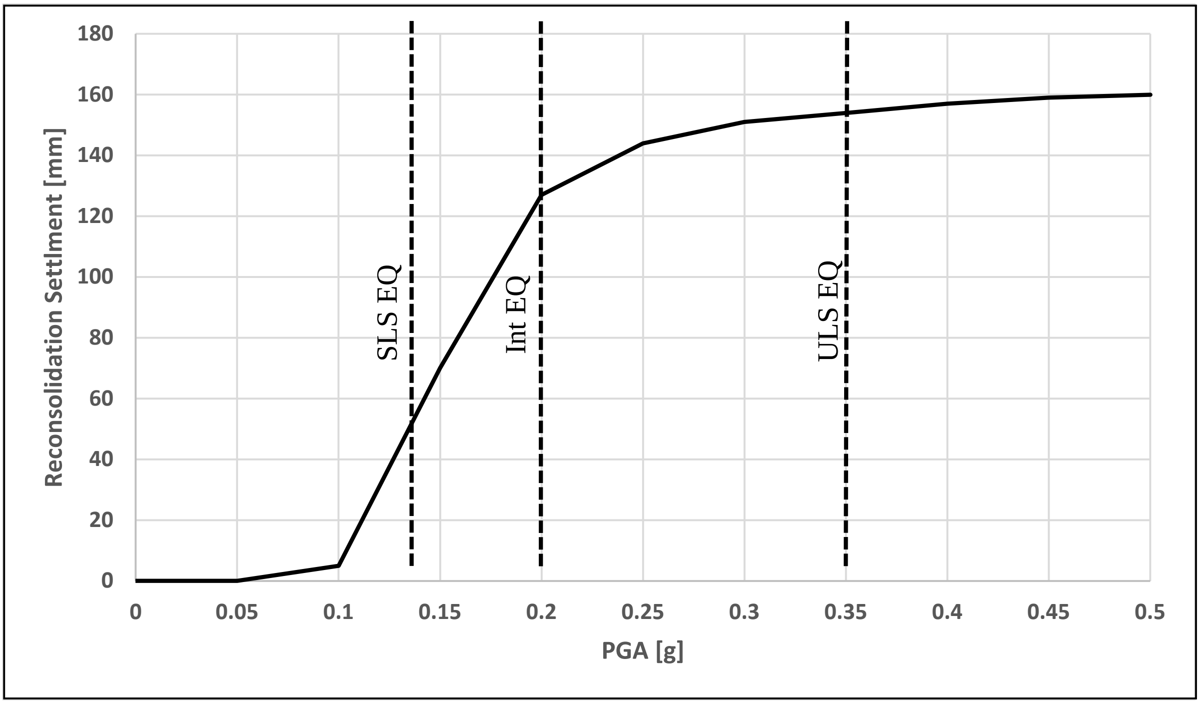

Figure 2 – Reconsolidation Settlement over the upper 10m with PGA St Martins Supermarket

In terms of rebuilding and going forward, Foodstuffs assessed the requirements for earthquake resilient buildings, which may suffer some superficial damage in future major earthquakes, balanced against the requirements for business continuity. Paramount above this was the safety of staff and customers. Due to the Owner/Operator nature of the Cooperative and its supermarket operations, the social and economic well-being of the communities they serve is an important aspect of determining the appropriate level of earthquake resilient building requirements. As had been experienced in the Canterbury and Christchurch earthquakes, the loss of a supermarket within a community has long lasting impacts well beyond the loss of business. The disruption to employment and the emotional aspect of disruption to the social environment, were all relevant factors that required consideration.

All Foodstuffs buildings and plant are insured, however there are limits on the amount of affordable Business Interruption cover that can be obtained. This restriction and the past experiences were pivotal in Foodstuffs deciding on the level of earthquake resilient buildings to construct. Added to this, Foodstuffs with its large market share, plays a major role in society through the importation, supply and distribution of foodstuffs, none more so than in the aftermath of an actual disaster. For these reasons, Foodstuffs sought to mitigate the effects of liquefaction at the key sites it was rebuilding. Foodstuffs had several supermarket sites with liquefaction measures already in place in their foundations and having these come through the earthquakes relatively unscathed, apart from minor cosmetic damage, reinforced Foodstuffs' desire to mitigate the effects of liquefaction.

7 REBUILD SOLUTIONS ADOPTED

In terms of liquefaction risk mitigation for a building there are four basic approaches:

1. Accept the risk of future liquefaction and deal with the damage in the future if and when an earthquake occurs.
2. Strengthen the structure well above the minimum code requirements to withstand the effects of liquefaction, for example founding it on deep piles or robust raft foundations.

3. Undertake ground improvement works to remove/limit the susceptibility of liquefaction and associated risk and construct a code level building.
4. Move to an alternative site with a lower liquefaction potential.

In order to meet Foodstuffs' business and resilience goals the first option of 'accepting the risk' was not adopted due to the disproportional level of damage liquefaction causes compared to ground shaking alone and the associated business disruption and costs that this damage causes. Due to the business need to have the supermarket where the people are and the highly competitive two player supermarket industry, the fourth option of abandoning the site and moving to an alternative site location was also not adopted.

Therefore the 'building strengthening' and 'ground improvement' approaches were considered for the four rebuilds. The liquefaction mitigation measures adopted by Foodstuffs' and the rationale behind these solutions are outlined in Table 2 below.

Table 2. Adopted liquefaction mitigation measures

Site	Liquefaction mitigation measure	Reasoning for solution
Kaiapoi	Stone Column ground improvement	The primary cause of liquefaction damage was the global lateral spreading and stretch towards the nearby Kaiapoi River. The 3m thick non-liquefied crust wound have enabled the use of a raft foundation system from a settlement and bearing capacity perspective but this would have still been susceptible to significant lateral spread damage. A block of stone column treated ground, formed with top driven 800mm diameter stone columns, was created below and beyond the building footprint down to the underlying gravel layer at 4m to 8m depth to effectively fully suppress both liquefaction and lateral spreading.
St Martins	19m deep CFA concrete piles	The primary cause of damage was foundation failure and punching into the shallow liquefiable soils. A raft foundation was not viable due to the lack of non-liquefiable crust. Ground improvement was not viable due to the building position hard on two boundaries and the sensitive (noise & vibration) urban setting. Therefore the building was founded on 149no. 750mm dia CFA concrete piles founded into the underlying dense gravel layer at 19m depth.
Redcliffs	6 to 20m deep bored concrete piles	The site is underlain by estuarine deposits overlying rock at 4m to 17m depth. A raft foundation was not viable due to the lack of non-liquefiable crust and expected +300mm differential settlement due to the dipping rock head and variable thickness of liquefiable soils. Ground improvement was impracticable due to the geological conditions and building location on the corner of the site. Therefore the building was founded on a combination of 80no. 406mm dia steel tube, and 900mm and 1,050mm dia bored concrete piles socketed at least 3m into the underlying rock. Variable pile diameters was used to get a 'balanced' structural response from the variable pile lengths.
Wainoni	Stone column ground improvement	The primary cause of damage was foundation punching into the shallow liquefiable soils and differential settlement with significant damage at only moderate levels of shaking. A raft foundation was not likely to provide sufficient foundation stiffness due to the size of the building (6,500m^2). Piles could not be used due to the lack of a piling bearing layer. Therefore a block of stone column treated ground, formed with 600mm diameter screw installed stone columns, was created below and beyond the building footprint to form a 9m thick non-liquefied crust to prevent shallow punching failures, minimise global differential settlements and prevents lateral spreading into the adjacent stormwater attenuation basins. Due to the sensitive urban site setting a 'screw' based installation methodology was utilised in order to minimise any construction vibration and noise from the stone column installation process.

For piled sites where ground settlement was still expected. To accommodate this ground settlement fully suspended floor slabs have been constructed to span between piles to protect the floor slab. At stone column ground improvement sites the foundation systems comprise shallow footings integrally connected to the double reinforced floor slab. A 0.5m thick gravel drainage blanket is installed between the top of the stone columns and below the floor slabs to drain any excess earthquake generated pore pressures and channel any surface ejecta away from underneath the building.

For all sites the treatment and protection of the underfloor services which are essential to the functionality of a supermarket was critical. The adopted solution was typically to encase these services within, or structurally connect below, the floor slab to prevent differential movement between them and the building. Where the services exit the building footprint flexible connections are employed to allow some differential movement and easy access for repair if needs be following a future earthquake event.

Going forward the same liquefaction risk mitigation approach used for the rebuilt sites has being adopted by Foodstuffs for other new-build solutions. At two post-earthquake new-build sites with moderate liquefaction susceptibility, raft foundations and shallow geogrid reinforced gravel capping layers have been constructed to minimise the likelihood of shallow foundation failures and differential settlement induced building damage and maximise ease of building repair and future re-levelling if required.

8 CONCLUSIONS

During the major seismic events of the Canterbury earthquake sequence liquefaction has caused disproportional large levels of damage to Foodstuffs' supermarket buildings compared to other sites on geotechnically more competent ground. Liquefaction induced ground damage has caused significant business disruption and losses in excess of the material building loss.

As part of the earthquake recovery and rebuild process extensive liquefaction mitigation measures have been invested in, and implement by, Foodstuffs, including founding buildings on; deep piles, ground improvement and raft foundations. With these mitigation measures in place, Foodstuffs have significantly increased their post-earthquake business resilience.

The benefits to Foodstuffs will be many; firstly, business continuity, which will have the effect of lessening any disruption to ongoing operations, staff and local communities. Additionally the human side of disasters can be easily overlooked once the shock of the disaster is over, but there is long lasting emotional impacts from the loss of a local identity and service provided by a supermarket and it is this impact that Foodstuffs wishes to mitigate against over and above providing the minimum code level of structural performance.

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