Comparison of Liquefaction Mitigation Options: A Christchurch Case Study

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ABSTRACT: Following the 4 September 2010 M_w7.1 Darfield and 22 February 2011 M_w6.2 Christchurch earthquakes Foodstuffs South Island Limited constructed one new and two replacement supermarket buildings at three sites (Ilam, Kaiapoi, and St Martins) across the wider Christchurch Region. The three sites had varying degrees of susceptibility to seismically induced liquefaction and lateral spreading. As part of the detailed design and construction process different liquefaction mitigation measures were utilised for each site. The aim was to minimise the future liquefaction susceptibility and increase the post-earthquake resilience of each facility. Despite each supermarket building having essentially the same structural form and footprint, the liquefaction mitigation measures employed were specific to each site and addressed the local liquefaction hazard, as well as local site geology and construction restrictions. This paper presents three case studies. It details the local geology and means of investigation, and outlines the liquefaction mitigation measures utilised and details the construction methods. The three ground improvement methods used were a composite geogrid reinforced gravel and reinforced concrete raft foundation system at the Ilam site; a ground improvement system using stone columns at Kaiapoi site; and bored concrete piles using a CFA method at St Martins site. It also outlines the reasoning for utilising each liquefaction mitigation method, the detailed design considerations and how each system performed during and after a major seismic event.

1 INTRODUCTION

1.1 Project Descriptions

Following the 4 September 2010 M_w7.1 Darfield and 22 February 2011 M_w6.2 Christchurch earthquakes Foodstuffs South Island Limited (Foodstuffs) constructed one new and two replacement New World Supermarket buildings at three sites (Ilam, Kaiapoi, and St Martins respectively) across the wider Christchurch Region. Refer to Figure 1 below for site locations. The three sites had varying degrees of susceptibility to seismically induced liquefaction and lateral spreading. As part of the detailed design and construction process different liquefaction mitigation measures were utilised for each site. The aim was to minimise the future liquefaction susceptibility and increase the post-earthquake resilience of each facility. Despite each supermarket building having essentially the same structural form and similar footprint area, the liquefaction mitigation measures employed were site specific to address the local liquefaction hazard, as well as local site geology and construction restrictions. The geological site conditions, liquefaction mitigation measures employed and site performance throughout the major seismic events of 2010 and 2011 are outlined in this paper below.

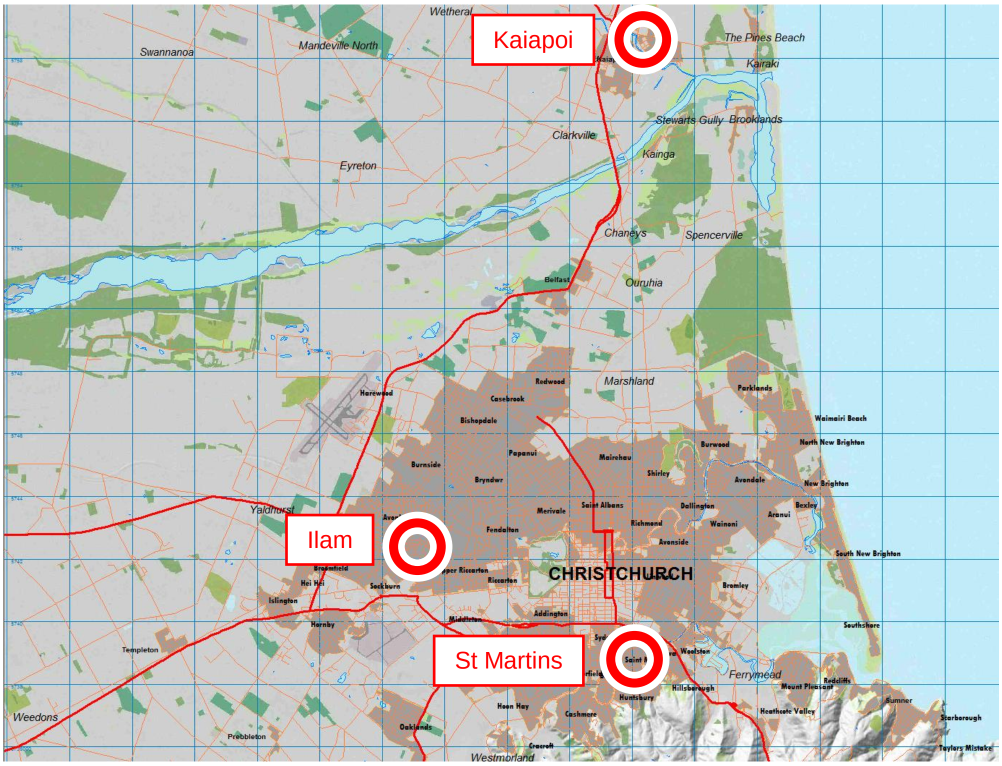

Figure 1. Site Locations

2 SITE SETTING AND LIQUEFACTION RISK

2.1 Ilam

Following the 4 September 2010 Darfield Earthquake (EQ) a series of eight Piezocone Penetrometer Tests (CPTu) were undertaken below the building footprint of the proposed new supermarket building. Additionally, a review of already undertaken shallow site investigation (hand augers and Scala penetrometer testing), and directly adjacent Environment Canterbury (ECan) borehole logs was completed. Monitoring of the shallow groundwater level from several standpipe piezometers located across the site was undertaken. The liquefaction hazard assessment for the site was based primarily upon the CPTu logs. Based upon the site investigation and liquefaction assessment the site was identified as being underlain by:

- Surface to 15m – Interbedded lenses and layers of potentially liquefiable loose to dense silty-sand, and non-liquefiable firm to stiff silts and clayey-silt material, overlying
- 15m onwards – Sandy-Gravel material.

Groundwater was located at shallow depths less than 1m deep. The site is not located immediately adjacent to any free edges such as waterways and there are no significant slopes present.

The liquefaction hazard assessment indicated that minor to moderate settlements could be expected at the site during a major seismic event with the calculated settlements in the order of 50mm under a Serviceability Limit State (SLS) design EQ and up to 100mm under an Ultimate Limit State (ULS) design EQ.

There were minor surface expressions of liquefaction at the site following the 22 February 2011 Christchurch EQ and the aftershock on 23 December 2011. The calculated site seismic demand at the site during each of the major seismic events is summarised in Table 1 below. The observed site behaviour was in general accordance with the calculated site behaviour from our free-field liquefaction hazard assessment.

2.2 **Kaiapoi**

The original Kaiapoi New World Supermarket was structurally damaged beyond economical repair as a result of the Darfield EQ. Damage was primarily caused by the effects of liquefaction induced settlement and lateral spreading and stretching. Several hundred millimetres of differential settlement and lateral stretching were recorded within the supermarket building. The Canterbury Geotechnical Database (CGD, 2012a) indicates that following the Darfield EQ the site settled in the order of 100mm and approximately 0.7m of lateral spread towards the Kaiapoi River, with approximately 0.5m of lateral stretch recorded across the site. Further liquefaction induced ground damage was observed at the site or in the immediate surroundings following the Christchurch EQ and to a lesser extent following the major aftershocks of 13 June and 23 December 2011.

Following the Darfield EQ a series of eight CPTu and two boreholes with Standard Penetrometer Testing (SPT) were undertaken around and below the footprint of the replacement supermarket building as part of the design process. A liquefaction hazard assessment was undertaken utilising the CPTu and borehole logs. Based upon the site investigation and liquefaction hazard assessment the site is underlain by:

- Surface to 4-7m – Interbedded layers of liquefiable loose to medium dense sand, silty-sand, and some silt (this layer is thicker towards the Kaiapoi River), overlying
- 4-7m onwards – Non-liquefiable dense to very dense sandy-gravelly material.

Groundwater was located at depths typically between 2 to 3m and varied with tidal fluctuations in the Kaiapoi River, which is located approximately 100m southwest of the site. The channel of the river is incised approximately 4m below ground level at the site.

The liquefaction hazard assessment indicated that moderate to major settlements could be expected at the site during a major seismic event with the calculated settlements >50mm under a SLS design EQ and >100mm under an ULS design EQ. Additionally, significant lateral spreading and stretching, in the order of hundreds of millimetres is expected across the site during a ULS design EQ event.

2.3 **St Martins**

The original St Martins New World supermarket was structurally damaged beyond economical repair in the Christchurch EQ from the effects of liquefaction induced differential settlement. Following the earthquake a series of 12 CPTu and five boreholes with SPT were undertaken across the site as part of the design process for the replacement supermarket building. A liquefaction hazard assessment was undertaken utilising the CPTu and borehole logs. Based upon the site investigation and liquefaction hazard assessment the site is underlain by:

- Surface to 14m – Interbedded layers of typically liquefiable loose to medium dense sand, silty-sand, some silt material and an intermediate gravel layer present over parts of the site, overlying
- 15m onwards – Non-liquefiable dense to very dense sandy-gravel material with some pockets of sand or clayey-silty material.

Groundwater was located at shallow depths less than 1m deep. The site is not located immediately adjacent to any free edges such as waterways and there are no significant slopes present.

The liquefaction hazard assessment indicated that moderate to major settlements could be expected at the site during a major seismic event with the calculated settlements in the order of 100-200mm under an ULS design EQ.

Following the Christchurch EQ the original shallow founded supermarket building exhibited differential settlement in the order of hundreds of millimetres across the footprint. Further liquefaction induced ground damage was observed at the site following the major aftershocks of 13 June and 23 December 2011.

2.4 Major Seismic Events - Ground Accelerations

The estimated ground accelerations for each of the major seismic events of the Canterbury earthquake sequence at each site, as recorded in the Canterbury Geotechnical Database (2012b), are presented in Table 1 below.

Table 1. Summary of Recorded PGAs.

Site	M_w7.1 4 September 2010	M_w6.2 22 February 2011	M_w6.0 13 June 2011
Ilam	0.23g	0.29g	0.16g
Kaiapoi	0.23g	0.19g	0.10g
St Martins	0.24g	0.56g	0.26g

3 LIQUEFACTION MITIGATION TECHNIQUES

Despite each supermarket building having a similar size, shape and structural form the liquefaction mitigation measures employed at each site were site specific and addressed the local liquefaction hazard, as well as local site geology and construction restrictions. This section outlines the chosen liquefaction mitigation measures and the reasoning for selecting the particular mitigation measure. Each of the liquefaction risk mitigation measures selected was chosen to minimise the likelihood of significant foundation and under floor service damage, hence maximising the post-earthquake resilience of each supermarket building.

3.1 Ilam

The Ilam site was investigated and designed following the Darfield EQ, with construction beginning before the Christchurch EQ. Following the investigation and analysis process, the site was identified to have a minor to moderate susceptibility to liquefaction in a future major seismic event despite no surface manifestations of liquefaction occurring at the site as a result of the Darfield EQ.

The liquefiable soils at the site were identified as being confined to discreet thin lenses and layers within the upper soil profile only. Due to a lack of a free edge at the site there was low risk of lateral spreading. The new supermarket building was founded on a composite geogrid reinforced gravel / reinforced concrete raft foundation system. This foundation system comprised of a triple reinforced (with geogrid at 250mm centres) 750mm thick geogrid reinforced gravel raft, with a approximately 300mm thick reinforced concrete rib raft founded directly on top of this. Above the rib raft is a 150mm thick post-tensioned concrete wear slab. In high load areas the rib raft required localised concrete thickenings. Generally the geogrid reinforced gravel section of the raft was extended 3m beyond the building footprint. Underfloor hydraulic services and conduits were protected in the building by embedding them within the raft foundation. Penetrations of any services below the raft were kept to an absolute minimum. See Figure 2 below for a typical view of the gravel raft under construction.

The purpose of this composite raft system is to reduce the liquefaction induced differential settlements and effectively dampen the effects of liquefaction felt by the structure; hence reduce the likelihood of structural damage. This solution does not stop liquefaction but reduces the effects of it to a level where the structure can withstand it. The geogrid reinforced gravel raft effectively works to reduce differential settlements by:

- Spanning across settlement induced hollows, and weak spots

- Dilating when sheared thereby expanding in the process of moving and settling
- The 3m wings effectively lengthen the flow path of any ejecta material from immediately below the building, thereby reducing the amount of material lost (hence settlement) below the raft.

Figure 2. Geogrid reinforced raft under construction showing layered construction methodology

To maximise these liquefaction mitigation effects the gravel raft was formed from a crushed AP40 material with at least two broken faces compacted to 98% of maximum dry density. This resulted in typical in situ dry densities in the order of 2,300kg/m^3. The geogrid and basal geotextile were Tensar TriAx TX160 and Bidim A19.

The geogrid reinforced gravel section of the raft was constructed in the dry in order to achieve the high installation compactions of the AP40 material. As such due to the shallow groundwater level at the site and to minimise construction issues, such as dewatering etc. the entire building ended up being raised by 200mm to ensure the base of the foundation excavation was above the ground water level.

3.2 **Kaiapoi**

The Kaiapoi site was investigated and designed in the spring of 2010, with construction commencing within three months of the Darfield EQ but prior to the Christchurch EQ. Following the site behaviour in the Darfield EQ, and the investigation and analysis process, the site was identified to have a major susceptibility to liquefaction and associated lateral spreading and stretching in a future major seismic event.

The liquefiable soils at the site were identified as being located within the saturated loose to medium dense sand, silty-sand material located in the upper 4 to 7m of the subsoil profile. Due to the presence of the Kaiapoi River channel 100m to the southwest of the site there is a significant risk of lateral spreading at the site following a major seismic event. In the area where the new supermarket building was constructed extensive ground improvement works were undertaken to create an approximately 75m long by 50m wide block of treated ground with very low liquefaction susceptibility. The intent of the ground improvement works is to create a monolithic block of treated soil that will limit settlement during a major seismic event and resist lateral spreading so as to protect the new supermarket building.

The ground improvement works comprised a grid of top driven stone columns utilising a dry installation method on a regular triangular grid pattern. The stone columns were installed to a depth where they were keyed approximately 0.5m into the top of the underlying gravel layer located at typically 4 to 7m depth. The ground treatment typically extended approximately 5m beyond the building footprint. On top of the stone columns a 500mm thick drainage blanket of crushed stone material was installed. The drainage blanket has been installed to act as a preferential drainage path for any excess pore water pressure and associate ejecta material that may drain out of the columns in a major seismic event. The building is then founded directly onto this block of treated ground using a ‘normal’ robust shallow footing reinforced concrete foundation system.

The stone columns are designed to suppress liquefaction through a combination of ground densification and stiffening. The ability for the stone column to reduce liquefaction susceptibility through drainage was not taken into account in design as the drainage properties of the columns are heavily affected by the installation process, and it is unknown how many liquefaction cycles the columns could act as drains for before clogging with silty-sandy ejecta material. Consideration to sleeving stone columns in geofabric was given but rejected due to the chosen installation method. To provide additional robustness the foundation system (particularly in the above code level EQ scenario), the columns also have the capacity to act as load transfer columns to the gravel layer located at 4 to 7m depth (similar to stone columns designed to axially reduce settlements in soft cohesive soils).

3.3 **St Martins**

The St Martins site was investigated and designed in the first half of 2011 following the Christchurch EQ. Following the observed site performance in the Christchurch EQ, and our site investigations and analysis, the site was identified to have a major susceptibility to liquefaction in a future major seismic event.

Ground improvement as a liquefaction mitigation option was ruled out at the site due to the depth of liquefiable soils, the requirement to have the building located on the corner for the site so ground improvement could not be extended beyond the building footprint, and the lack of any available ground improvement equipment suitable to be used in an urban environment. Due to this, it was decided to found the building on bored reinforced concrete piles embedded well into the underlying gravel layer. To minimise construction noise and vibration in the urban environment the technique of Continuous Flight Auger (CFA) piling was utilised. This piled foundation system does not suppress seismically induced liquefaction, but transfers structural loads from the supermarket building to the underlying non-liquefiable gravel layer.

In order to provide post EQ resilience to the building and its on-going operations the piles were essentially designed to withstand a worst case scenario of fully code level seismic shaking in fully liquefied ground conditions. This is to conservatively model the effect of a major aftershock while the site is still in a fully liquefied state. Due to a lack of strength and stiffness in liquefied soil, the piles are effectively designed to transfer base shear from the building into the underlying gravel layer through mechanical bending. Due to this design requirement, the governing design load is lateral loading not axial loading. The finalised design called for 143 750mm diameter piles founded at 19m depth, which reflects this lateral loading requirement. The piles have been designed as ‘fixed-head’ piles to minimise the bending loads by putting the piles in double bending. Pile head fixity is achieved through the piles heads being set into a grid of robust ground beams.

As the ground below the building site is expected to settle following a major EQ due to the effects of liquefaction, the floor system has been designed to fully span from ground beam to ground beam. Also to protect under floor hydraulic services and conduits etc. these have been fully encased and structurally connected to the underside of the floor slab. As significant liquefaction ejecta material is expected in a major EQ, to further protect the floor slab a 500mm thick drainage blanket has been installed below and 2m beyond the building footprint to act as both a reservoir and to provide a preferential drainage path from below the building footprint.

4 **2011 EARTHQUAKE PERFORMANCE**

4.1 **Ilam**

At the time of the Christchurch EQ the gravel raft section of the foundation system was effectively at full thickness across approximately two-thirds of the building footprint. Sand boils and surface ejecta were observed at localised spots across the site, with a concentration of ejecta along several edges of the raft. However, no liquefaction ejecta was observed to have penetrated through the gravel raft.

A level survey following the EQ indicated that the top of the gravel raft had not moved as a result of the EQ. The CGD indicated that the site experienced a PGA of 0.29g during the Christchurch EQ. As such this event was effectively smaller than the ULS design EQ. However, this EQ was sufficiently large to be a significant test and hence reinforce the expected positive foundation performance during a future large scale liquefaction inducing seismic event.

Some minor ground damage or surface manifestation was observed at the site during the December 2011 major aftershock. Despite no PGA values being available for this event at the site, this earthquake event was effectively equivalent to the SLS design EQ event. As such, it provided a test of likely performance which resulted in no known foundation damage.

4.2 **Kaiapoi**

At the time of the Christchurch EQ only a small number (approximately 20%) of the stone columns had been installed as a perimeter strip. Therefore the full ground improvement effects of the columns could not be realised. Further minor surface expression of liquefaction was observed in parts of the site and the surrounding properties, while in the area of the treated ground no ground damage occurred. The ability for the columns to act in drainage was observed with significant ejecta material coming out of some columns (see Figure 3 below). However, following the Christchurch EQ several of the stone columns were noted to be clogged with silty sandy material. As such, the design consideration of ignoring the drainage capacity of the stone columns was assessed as being prudent as it is unknown how well these columns would act in drainage following a future major EQ now they are contaminated with silty and sand material. Following the 13 June and 23 December 2011 major aftershocks no ground damage was reported at the site, with minor surface expression recorded at nearby sites.

Figure 3 – Photo of Stone Column at Kaiapoi following Christchurch EQ showing drainage ejecta

The CGD indicated that the site experienced a PGA of 0.10g during the 13 June 2011 major aftershock. As such this event was effectively a SLS design EQ. As such, they were a limited test of likely performance per se. This was similar again for the 23 December 2011 major aftershock. However, this lack of ground damage at the site during these major aftershocks is consistent with the SLS design philosophy, i.e. no damage occurring during a SLS event.

As such the liquefaction mitigation measures employed in the new Kaiapoi New World Supermarket have not yet been fully tested.

4.3 St Martins

At the time of the 13 June 2011 major aftershock the original supermarket building was still being deconstructed. Further surface expression of liquefaction occurred at the site during this EQ. At the time of the 23 December 2011 major aftershock the piles had been installed and parts of the foundations completed. However, no building superstructure had been erected at the site. Again further minor surface expression of liquefaction occurred at the site during this EQ. It is noted that, this site response post pile construction is consistent with the design philosophy of strengthening the building foundations to withstand the effects of liquefaction, not suppressing it.

As such the liquefaction mitigation measures employed in the new St Martins New World Supermarket have not yet been effectively tested.

5 CONCLUSION

The three supermarket sites outlined in this paper have all been identified as having varying susceptibilities to seismically induced liquefaction. Despite each supermarket building having essentially the same structural form and similar footprint area each development has utilised quite different site specific liquefaction hazard mitigation measures as part of their (re)development in order to provide post EQ resilience to the supermarkets. The liquefaction mitigation measures used were a composite geogrid reinforced gravel and reinforced concrete raft foundation system at the Ilam site; a ground improvement system using stone columns at Kaiapoi site; and bored concrete piles using a CFA method at St Martins site. During or post construction, each of the sites has experienced at least one major seismic event that has provided, to various degrees, a test of the chosen liquefaction mitigation measure utilised. During these events the liquefaction mitigation measures have performed successfully and reinforce the expected positive foundation performance during a future large scale liquefaction inducing seismic event.

6 ACKNOWLEDGEMENTS

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7 REFERNCES

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