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Human centric design of resilient foundation systems

J. Kupec & D.P. Mahoney
Aurecon New Zealand Ltd., Christchurch, New Zealand

R. Parish
Foodstuffs South Island Ltd., Christchurch, New Zealand

ABSTRACT: Foodstuff South Island is one of the largest providers for groceries in New Zealand. Foodstuffs manage dozens of retail stores in the Canterbury Region of New Zealand and their supermarket network extends across the entire South Island. Their building portfolio, albeit fully compliant with the New Zealand Building Code, performed poorly after the Canterbury Earthquake Sequence. The principal cause for poor performance was excessive unrepairable foundation damage. Whilst several stores and distribution centres were severely damaged in the initial earthquake, others suffered from progressive deterioration as aftershocks continued. Repairs, reconstructions and new builds were part of the decade long rebuild process. Key part of the rebuild was to maintain the same building typology to ensure a consistent portfolio look and streamline construction. This in turn necessitated modification of the foundations and/or the ground to enable the similar building topology to be constructed on top of it despite grossly different ground performance. This paper will by way of example illustrate typical earthquake damage to the light commercial buildings, with focus on their foundations performance. The authors will discuss the asset owner's need to provide much higher building resilience to avoid future earthquake damage, but also to ensure business continuity and safeguard access to food and general supplies after a major natural disaster. The paper will provide design details for a wide range of sites with different vulnerability to seismically induced ground damage. The foundation options will include sites with ground improvement using stone columns, geogrid reinforced load transfer platforms, large diameter bored concrete piles, steel screw piles, RibRafts and tied grillages of ground beams as well as shallow footings. The main aim of this paper is to discuss how foundation solutions, for essentially the same building, address the highly variable ground conditions and how a human centred approach directed the adopted design solutions.

1 INTRODUCTION

The Canterbury Earthquake Sequence (CES) impacted the New Zealand economy. The property damage alone was estimated to be over USD40b, which is 40% of the GDP (gross domestic product) of New Zealand. The loss and damage to the overall residential and commercial building portfolio impacted on the community of Greater Christchurch, and to some degree, eight years on, is still felt. This paper focus on grocery retail store building damage caused by seismically triggered liquefaction and how loss and damage of buildings and subsequent rebuilding of the portfolio impacted the wider community. Case studies of rebuild projects will by way of example demonstrate the measures taken to ensure a more resilient building portfolio. The building portfolio is owned by the Foodstuffs South Island Ltd cooperative, one of two major grocery distributors in New Zealand. Aurecon engineering specialists worked alongside Foodstuffs staff to assess property damage, prepare repair or where appropriate design rebuild solutions. We will discuss the impact on the community and what steps were taken to approach the recovery from a human centric attitude.

2 CANTERBURY EARTHQUAKE SEQUENCE

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.

Significant lateral spreading damage occurred along the banks of the Avon and Heathcote Rivers in the east of the city and around the Kaiapoi River to the north of the city in the township of Kaiapoi. Ground shaking was higher in the west and north during the Darfield Earthquake and in the east during the Christchurch Earthquake. Peak ground accelerations (PGA) typically between 0.2g and 0.5g were experienced at Foodstuffs retail stores across the city during both earthquakes, (Bradley & Hughes, 2012a) and (Bradley & Hughes, 2012b).

At the time of the earthquakes Foodstuffs' building stock within the Christchurch region were typically built in the 1970's through to early 2000's. Most of these buildings were founded on simple shallow pad and strip foundation systems with lightweight floor slabs which were often floating and not always integral (connected) to the shallow foundation system. However, some buildings were founded on piles or extra wide strip footings with integral floor slabs spanning between supports acting much like a raft foundation. Supermarket retail 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 some 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.

3 DAMAGE TYPES

From Foodstuffs perspective the Canterbury Earthquake Sequence caused varying damage to their building stock throughout the city. In summary we found that better building performance was found, where:

- The ground was better (typically on the western side of the Christchurch region with shallow gravel layers and deeper water table) or
- Where the ground shaking was of a lower intensity or
- Specific regard had been taken to account for seismically induced liquefaction in the building design.

Retail stores on these sites were functioning in the order of hours, to few days, following major earthquakes and overall the buildings performed well from a seismic engineering perspective. In the CES and subsequently during the 16 November 2016 M_w7.8 Kaikoura Earthquake, seismic damage typically manifested as structural damage with little to no foundations movement.

Less optimal building performance was generally found, where:

- The ground performance was poorer (typically on the eastern side of Christchurch) where loose saturated silty-sandy soils and high water table are present and
- High ground accelerations were recorded and
- Shallow foundations system with no specific regard for liquefaction mitigation were prevalent, (Kupec & Mahoney, 2013).

Significant building damage occurred with a major portion of this damage attributed to the effects of shallow liquefaction causing foundation bearing failures expressing as excessive settlements that in turn lead to significant structural damage, (Mahoney & Kupec, 2014).

Additional, and often severe, building damage occurred where in addition to liquefaction, lateral spreading occurred towards free edges, such as channels or rivers. In the case of Kaiapoi store, lateral spreading occurred towards the 120m distant river edge, which in turn caused in excess of 300mm lateral stretch across the building footprint causing significant structural damage (Mahoney & Kupec, 2013). All sites exhibiting major to severe lateral spreading required major repair works such as building re-levelling, or demolition and rebuild.

Rebuilding replacement structures was often taking over 18 months with associated business and social disruptions. Of the stores requiring complete replacement or major repairs, all were on shallow foundations and none of the initial designs took account of seismically triggered liquefaction and its associated effects. However, all structures complied with the New Zealand Building Code at the time of their construction. The sites that suffered extensive ground damage were all in areas that have been subsequently associated with the highest liquefaction hazard rating. The noticeable exception to poor building performance on liquefiable sites was the Halswell store dating to the early 2000's. This structure was founded on a quasi-raft type foundation system as the soils had lower bearing capacities. This site was subject to high seismic shaking and it exhibited moderate liquefaction and ground damage during the Darfield Earthquake. However, the store suffered no geotechnical induced damage, while the neighbouring retail stores founded on isolated shallow footings did suffer reasonably significant liquefaction induced foundation and building damage. This differing response between a well tied together robust raft or isolated shallow foundations illustrates the impact liquefaction mitigation measures can make in building performance.

4 IMPACT

The impact from the earthquakes to the community was profound. The city of Christchurch was not generally considered to be at a high earthquake risk, compared to say New Zealand's capital of Wellington. The severe shaking and subsequent loss of life and property damage caused a widespread disruption, that to some degree continues, some eight years after the initial earthquake in 2010. From a building portfolio owner and major contributor to employment in generally lower social economic areas, Foodstuffs building damage impacted a large number of people.

Foodstuffs operates as a cooperative and their retail stores are run using an owner-operator scheme. Damage or total loss of a retail store had a direct impact on the cooperative, the shop owners and their employees and customers.

The grocery retail market in New Zealand is highly competitive and customers were at risk to seek other retail stores and migrate away during prolonged shut downs for repairs or building replacement. Especially as repairs or replacement of the retail stores took on average 18 months per store. Woolworths, competitor of Foodstuffs, generally had retail stores in very similar locations and their building portfolio followed very similar design approach and subsequently suffered very similar building damage and loss. Not all stores were able to be immediately repaired or replaced due to a number of issues; chief amongst the delays was availability of engineering and construction resources.

The community was disrupted, often over a longer term, by the interruption in supply of groceries due to loss of a retail store or distribution centre. Store closure, even temporary for duration of the repair, created localized unemployment with associated disruption to social fabric. This highlighted the dependency of local community on their access to groceries and employment. It is worth noting that an average supermarket can employ up to 100 staff, generally in the lower socio-economic community reliant on nearby employment.

Foodstuff and their engineering advisors attempted to enable temporary repairs to stagger retail store reinstatement and replacement. For example, the large Wainoni retail store was fully rebuild on the adjacent car park to allow the continued operations of the earthquake damage retail store. This created constraints not generally encountered in the New Zealand construction industry that is more used to ‘green field’ developments.

Foodstuffs identified a risk to their ongoing business operations. They also accounted for the adverse impact the loss of a retail store has on the adjacent community. To address those risks, they sought specialist engineering advice to provide resilience to their business operations. As part of the rebuild programme and new construction as part of the wider expansions in New Zealand, Foodstuff now consider post disaster building resilience critical to their business operations. In summary, all new-builds, and where major repairs were completed, now incorporate substantial additional resilience against geotechnical failures. The following sections detail some of the key geotechnical solutions used to provide additional, above the New Zealand Building Code performance.

5 GEOTECHNICAL SOLUTIONS FOR RESILIENT BUSINESS

The New Zealand Building Code (NZBC) typically requires buildings of the type and form of a supermarket to be designed to withstand two levels of earthquake events. A Serviceability Limit State (SLS), a 1 in 25-year return period event, some damage is acceptable but no loss of amenity. This size event is expected to occur nominally twice during the design life of the structure. Ultimate Limit State (ULS) nominally a 1 in 1,000-year return period event is primarily concerned with life safety, structural damage and component damage is expected, ideally repairable, but no collapse of the structure shall occur. There is nominally a 5% chance of this event occurring during the design life of the structure. The key assumption NZBC makes, is that the level of structural damage is expected to linearly increase with the increasing levels of ground shaking, i.e. from SLS to ULS.

In contrast, soil liquefaction has a brittle response with no liquefaction occurring until a triggering threshold of shaking is reached and then with only a small increase in shaking ‘full’ liquefaction will occur. Once liquefaction has occurred ground damage does not practicably get any worse with increasing levels of shaking. In the Christchurch setting the onset of liquefaction often occurs around the equivalence of 1 in 50-year return period earthquake (i.e. just above a SLS level) and ‘full’ ground damage occurring by the 1 in 100 to 1 in 150-year equivalent earthquake, i.e. ULS levels of ground damage at approximately 30% to 50% of ULS level ground shaking.

When compared to the New Zealand seismic loading standard (NZS1170.5) the ground shaking at the stores requiring rebuild was equivalent to the nominal 1 in 150 to 550-year return earthquake event, well short of the nominal 1 in 1,000-year design life safety (ULS) earthquake event for an IL3 structure as per NZBC.

Based on the CES experience stores located on sites with good ground structurally outperformed sites on poorer ground. Therefore, form a structural perspective the intent of the NZBC is being meet with ‘normal’ structural design. However, at geotechnically poor sites without specific and often significant geotechnical mitigation the intent of the NZBC was not meet. Therefore, geotechnical design is a key element in providing the level of post-earthquake business resilience that Foodstuffs desire, and the community deserve.

To meet Foodstuffs’ intent for business resilience the geotechnical design needs to perform well in excess of the minimum NZBC requirements. In practice this means mitigating or significantly reducing liquefaction and associated effects from a SLS level event onwards. That way the structure is not adversely affected by excessive post liquefaction consolidation settlement and loss of foundation bearing. From a design and construction perspective there is practicably only one chance to embed resilience into the store and that is at the beginning of a project as there is no practicable way to retrofit foundation resilience.

Due to geotechnical variability the resilient foundation solutions were developed in a bespoke way on a case by case basis. The preferred solution for a given site is dependent on numerous geotechnical considerations and other site constraints (both physical and business operations related), with the key considerations and adopted solutions presented in Table 1 overleaf.

Table 1. Foundation options and types to manage liquefaction and lateral spreading hazards based on rebuild of Foodstuffs portfolio

Hazard class	Foundations	Services	Comments
No liquefaction	Standard shallow pad and strip footings well tied together	Standard underfloor service detailing	Typically used on sites with very competent (dense gravelly) soils, with deep water table. No specific geotechnical regard to floor slab detailing is required.
Limited liquefaction risk with discreet and limited lenses of liquefiable soils and limited (say <100mm @ ULS) post-earthquake ground settlement, but competent non-liquefiable crust (~2m thick)	Reinforced concrete raft foundation	Services structurally connected to the underside of the slab and kept above the footing level.	Slab is to be double reinforced to allow for bending. Ideally the raft can cantilever on an edge; and span unsupported the typical sand ejection crater widths or settlement throughs.
Continuous deeper liquefaction with a *thick non-liquefied crust* and limited post-earthquake reconsolidation settlement	RC raft foundation with localized geogrid reinforced gravel capping layer below heavily loading foundation areas	Services structurally encased to the underside of the floor slab.	Differential settlement and punching through crust into liquefiable soil will govern the foundation design.
Continuous deeper liquefaction and post-earthquake reconsolidation settlement but with a *thin non-liquefiable crust*	Shallow ground improvement (nominal 750mm thick gravel with three layers of high-strength, high-stiffness geogrid reinforcement) with a reinforced concrete raft foundation. Biaxial Naue Secugrid 40/40 Q1 was used as primary high stiffness geogrid reinforcement.	Services below the structural foundation level encased within the geogrid reinforced gravel layer. Care needs to be taken as services must be installed at the time of reinforced gravel raft construction.	Detailing of underfloor services can be difficult due to clashing with geogrid reinforcement. Ideally a service space between the geogrid reinforced graft raft and the structural concrete foundation is needed. The foundation system was shown to work well as it performed well during the Christchurch Earthquake, (Mahoney & Kupec, 2013).
Continuous deeper liquefaction with a very thin non-liquefied crust <u>and</u> *large post-earthquake reconsolidation settlement* (>100mm @ ULS)	Bored concrete piles with fully suspended floor slab, i.e. no support from the soil from below the piled raft is anticipated. Soil is anticipated to settle away from the underside of the floor slab.	Services structurally encased to the underside of the floor slab.	Due to the lack of a usable non-liquefied crust building base shear may not be resisted with ground beams and pile caps. Therefore, large diameter (750mm to 1,050mm) reinforced concrete piles are required to transfer building base shear down the pile shaft in bending. It is noted that this type of foundation

(*Continued*)

Table 1. (*Continued*)

Hazard class	Foundations	Services	Comments
			system is mechanically inefficient.
	Steel screw piles with deep ground beams and fully suspended floor slab, as above there is no reliance on the subsoil to provide any support.	Services structurally encased to the underside of the floor slab.	The building design must demonstrate that building base shear is able to be generated by pile caps or ground beams as screw piles offer very little bending resistance and are intended to carry axial stresses only.
Deep liquefaction (>10m) with large differential settlements (>100mm) and thin crust (<1m)	Deep (8–10m) stone columns fully suppressing liquefaction at ULS shaking levels. Well tied together shallow footings and integral floor slab acting as a raft foundation	Services structurally encased to the underside of the floor slab.	Due to building size deep ground improvement need to control differential settlement. The ground improvement block must be bigger than the building footprint. As sites are often located in suburban areas, low noise and vibration stone column or similar installation methods should be selected to minimise disturbance to the neighbours. Low vibratory ground improvement methods were successfully used in Christchurch where earthquake damaged stores were directly adjacent to structures being rebuild.
Lateral spreading hazard (generally the liquefaction hazard is high as well)	Deep stone column ground improvement with shallow foundations for full liquefaction and lateral spreading mitigation @ ULS levels of earthquakes	Services structurally encased to the underside of the floor slab.	Create a block of non-liquefied soil sufficiently large to prevent lateral spreading within the building footprint. The ground improvement footprint is larger, on average 3 to 6m beyond the building outline, as dictated by the depth of the liquefiable layer(s).

6 CONCLUSIONS & DISCUSSIONS

The Canterbury Earthquake Sequence clearly identified the role of the foundation system to resist seismically triggered liquefaction effects and prevent or reduce structural damage from settlement. Where ground performed poorly, and no specific measure were provided to resist loss of strength and/or lateral spreading was observed, foundations and consequently the structural system were severely damaged. In cases where mitigation for poor static ground performance were provided, such as tied together raft or grillages of ground beams, those were able to resist induced deformations and although not specifically designed for and provide better overall building performance.

Learnings derived from observing ground performance and how this affected the structure were used to derive higher resilience for new-build and rebuild solutions. Those were shown by way of example and tabulated against increasing level of anticipated ground damage. Foodstuffs rebuild or repaired their building stock. This included smaller supermarket retail stores, very large retail stores and distribution centres. The repaired and new building portfolio now features much higher resistance to seismically induced ground damage and therefore will provide higher resilience.

For Foodstuffs this has multiple benefits such as ability to continue business operations following large earthquakes, be able to make informed decision to insure their buildings and take measures to reduce business interruptions. Foodstuffs will be able to continue selling groceries and essential supplies post disaster, maintain their trained workforce and service their community. Their clients will not be forced to seek competing retailers and able to purchase their goods locally. Their distribution centres and warehousing will be less likely to lose essential supplies due to seismic shaking damage.

For the community the benefits are many. People can have confidence that the retail stores are ‘safe’ and able to resist large earthquakes and operate afterwards, thus ensuring that vital supplies are at hand and can be sourced from unaffected distribution centres and warehousing. Foodstuffs supermarkets are an important employer, often for untrained casual workers relying on local employment. Having the certainty to offer continued employment offers assurance and reduced vulnerability.

One may argue that Foodstuffs’ decisions to increase their building portfolio resilience was driven by commercial incentives. However, the business model of a cooperative is different and a human centred approach to recovery from a disaster was a key consideration. Foodstuffs decided to provide, as part of their building portfolio construction, significant above New Zealand Building Code resilience to ensure the community of which the Foodstuffs cooperative is part of is being looked after.

Implementation of geotechnical resilient solutions is now part of Foodstuffs building design outside of Christchurch to reduce their vulnerability of severe disruptions from seismic actions.

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