Development of Guidance Information for the Repair and Re-building of Houses Following the Canterbury Earthquake Series

Graeme J Beattie[1]

1. Principal Structural Engineer, BRANZ Ltd, Private Bag 50908, Porirua 5240, New Zealand. Email: graeme.beattie@branz.co.nz

Abstract

The two Canterbury earthquakes (9 September 2010 and 22 February 2011) had a devastating effect on the residential homes in many parts of Christchurch city and surrounding communities. The earlier event caused heavy liquefaction damage in suburbs located close the waterways resulting in distorted houses. The location of the second event exacerbated this problem and added the factor of short period high intensity shaking on hillside houses, combined with an extremely high vertical acceleration component. This resulted in severe shaking damage to the hillside communities.

This paper addresses the work initially undertaken by the Engineering Advisory Group (EAG) to the Department of Building and Housing (DBH) following the September event and the extension of this work following the February event, culminating in the publication of a Guidance document focusing on housing. In a short time period the Group developed processes for the assessment of liquefaction and spreading induced foundation damage against existing design criteria for new houses contained in the NZ Building Code and associated standards and produced guidance for the repair or re-building of houses to cope with possible future liquefaction events. A key issue was the high potential for liquefaction occurring in the near future in some areas, even in service limit state earthquakes.

Keywords: earthquake, houses, liquefaction, shaking damage, foundations

1. INTRODUCTION

The Canterbury earthquake series began with the 7.1 Richter magnitude event on 4 September 2010 and at the time of writing (more than 12 months after the first event) it is still on-going, although the number and magnitude of aftershocks is lessening, thankfully for the residents of Christchurch and surrounding communities. The second major event on 22 February 2011 (technically an aftershock and 6.3 magnitude) had much more dire consequences than the main event. Several other aftershocks resulted in further damage occurring, notably the 2010 Boxing Day shake and the magnitude 6.3 shake on 13 June 2011.

There were several characteristics of all events that were unexpected. While it was known that there were faults beneath the Canterbury plains, their exact locations were not precisely known. The extent of liquefaction was very significant and while the existence of liquefiable materials beneath the city was known, the consequences of the phenomenon were probably more severe than anticipated. Indeed, the public was largely unaware of what liquefaction was before 4 September but there would be few residents of Christchurch that could not associate with it now. The magnitude of vertical accelerations was very large in both the February and June events, particularly in the hill suburbs and the eastern suburbs on the flat.

This paper describes some of the observed damage to residential houses, the development of technical guidance information for the repair and replacement of house foundations affected by liquefaction in the September event and the re-assessment of this guidance and extension to cover shaking damage to house superstructures following the February event.

2. THE EARTHQUAKES

At 4:35am on 4 September 2010 a magnitude 7.1 earthquake struck the Canterbury region of New Zealand. While centred approximately 40km west of the centre of Christchurch, the shallow epicentre of the event (10km) meant that its effects were widely felt in Christchurch. A ground surface rupture occurred at Greendale, between the epicentre and the city. The major manifestations of damage in the Christchurch area were fallen unreinforced masonry chimneys (Figure 1), minor damage to internal linings of houses, some damage to old unreinforced masonry commercial buildings and the initiation of liquefaction (Figure 2). The liquefaction was generally confined to areas close to waterways and areas particularly badly hit were Kaiapoi (to the north of Christchurch), Bexley, Dallington and Horseshoe Lake. The issue was often compounded by lateral spreading of the ground towards the waterway. Little shaking damage to houses was observed in the hill suburbs. While not obvious to the casual observer, many industrial storage racking systems suffered very badly and there was also significant damage to building contents.

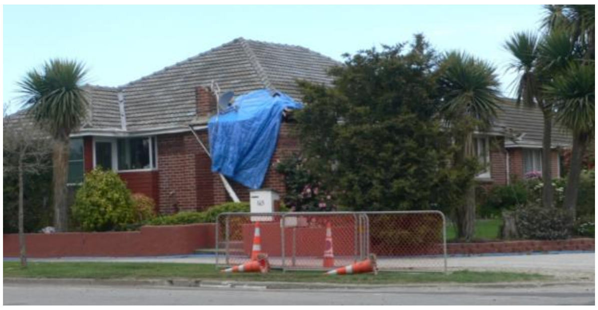


Figure 1 Collapsed unreinforced masonry chimney

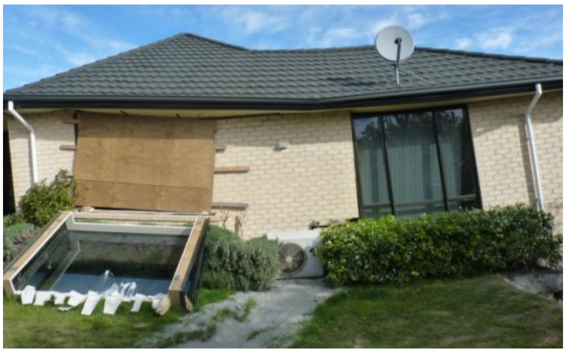


Figure 2 Liquefaction damage

While the second major earthquake on 22 February was a lesser Richter magnitude (6.3), its epicentre was much closer to the city, being centred under the port community of Lyttleton, and the epicentral depth was only 5km. Readers will be well aware of the disastrous consequences of this second major event. The close proximity to the central business district of Christchurch and the 12:51pm timing of the event meant a far greater exposure of lives, with 181 people perishing and 164 people seriously injured. Liquefaction damage extended over a far greater area of the city and shaking damage was pronounced on the Port Hills, to the southeast of the city centre.

3. ENGINEERING RESPONSE TO RESIDENTIAL DAMAGE

3.1 Post September 2010

Within days of the September event, a group of structural and geotechnical engineers was formed to assess the land and building damage and develop Guidelines for the reinstatement of land and repair and re-building of houses in Christchurch. The group included representatives from engineering consultancies (including Tonkin and Taylor), contractors, the Earthquake Commission (EQC), the Department of Building and Housing (DBH), BRANZ and the Structural Engineering Society of NZ (SESOC), and was referred to as the Engineering Advisory Group (EAG) to the DBH.

Tonkin and Taylor Ltd, geotechnical engineers, had consulted to the EQC prior to the earthquake on geotechnical matters and they immediately swung into action, assessing the land behaviour and designing coordinated land remediation measures covering areas close to waterways. The majority of the remediation works were going to be possible in road or public reserve areas with minimal effect on houses. The expectation of the proposed works was that future lateral spreading would be limited to manageable amounts.

To prevent the need for deep geotechnical investigations for individual properties the EQC commissioned suburb geotechnical investigations for the worst affected suburbs which would be made available for use with building consent applications for new dwellings. The residential area was thus sub-divided into three land zone categories:

Zone A – generally no land damage – repairing and rebuilding in accordance with NZS 3604 (SNZ, 1999) principals.

Zone B – some land damage suffered – repairing and rebuilding generally in accordance with NZS 3604 principals. Some re-levelling may be necessary.

Zone C – very severe or major land damage or areas close to areas of major remedial works. Badly damaged houses requiring replacement in areas where no remedial works were to be undertaken would require specific engineering design of the foundation system.

On an individual dwelling basis in these suburbs, reconstructed houses would only need to have a normal NZS 3604 geotechnical investigation. Such an investigation considered the normal static conditions and excluded the effects of liquefaction. The main purpose of the investigation was to confirm that the upper 2m of land met the NZS 3604 requirements of a 300kPa ultimate bearing capacity, expecting that liquefaction effects in a future event would be minimal.

However, for new foundations being constructed in areas where some land damage had been suffered and where suburb-wide land remediation work to reduce the future risk of lateral spreading was to be undertaken, the EAG proposed several generic design options for new concrete floors that provided a stiff platform. The aim was to ensure that in the event of possible further earthquakes, if any foundation settlement occurred then it would be a relatively simple task to re-level the dwelling. The foundations were designed to span over a 4m loss of support from within the footprint of the building or a 2m loss of support from the extremes of the floor (ie ends and outer corners). They would also be capable of resisting small amounts of lateral spread. Lifting systems available included screw piles around the perimeter of the foundation and the injection of grouts or engineered resins beneath the floor.

Minimal advice was given on the reinstatement of the superstructure of houses because most of the shaking damage was quite superficial in areas not affected by liquefaction and because the EAG was keen to have the foundation repair and rebuild information available quickly.

Several workshops were held with the insurance companies and their repair contractors, territorial authorities and engineers to gather feedback on the proposed approaches during the development of the guidance document and particularly to trial the decision parameters for determining whether, firstly, a re-level would be required and then if a foundation repair or rebuild would be necessary.

On 20 December 2010, the DBH published the results of the deliberations of the EAG in the document "Guidance on house repairs and reconstruction following the Canterbury earthquake" (DBH, 2010). The plan had been to publish a revision of the Guide in April 2011, where further guidance would be included on chimney repairs and replacements, concrete slab crack repairs and further revision of the original document would be included, as required, following its use over the intervening period.

3.2 Post February 2011

The event of 22 February 2011 altered the EAG's thinking for the future rebuild of the residential sector of the city. To put the event in perspective, the area of liquefied land increased tenfold. Some suburban areas settled up to 0.5m as a result of the ejection of liquefied sands and there was further evidence of lateral spread towards waterways. The peak ground acceleration (PGA) recorded in the east of the city was 1.9g (c.f. 0.3g in September) and on the Port Hills 2.2g (c.f. 0.6g in September). Furthermore, vertical accelerations, particularly on the Port Hills in February were much greater that had ever been expected to be designed for. The maximum recorded PGA was greater than 2g in some locations on the Port Hills.

3.3 Re-structuring of the EAG and Development of Land Zones

It took until April 2011 to get through the emergency phase following the February event and time and resources were again available to provide input into the development of guidance information. The original EAG was split into a residential EAG sub-group and a commercial EAG sub-group, as there was now a huge task involving assessments of thousands of commercial buildings and a consistency of approach was highly desirable. The number of members in the residential sub-group was similar to that in the EAG formed after the September event. This sub-group was tasked with revising and expanding on the guidance information published in December. The aim was to provide guidance on how the effects of liquefaction could be allowed for in the design and detailing of foundation repair and rebuilding, to provide greater resilience in future earthquakes.

Working for the EQC, Tonkin and Taylor set about mapping the extent of liquefaction over the city with field inspection teams going door to door. A similar but simpler process had been instituted following the September event. In the 2011 process a cursory inspection was also made of the damage to the dwellings on liquefaction and/or lateral spreading affected properties (pure shaking damage effects were excluded). Further information was gathered via the EQC building damage rapid assessment undertaken in March and April 2011.

Theoretical analyses of ground conditions and seismic hazard were combined with the predicted effects of earthquakes with potentially different characteristics. Key parameters in this analysis included the remnant thickness and strength of the surface crust of non-liquefiable material based on the groundwater depth the composition of the shallow soils (2-5m depth). Consideration was also given to the gazetted increase in the service and ultimate limit state level earthquakes' spectral accelerations for Christchurch. The aim of this process was to combine all of the observational data from September and February with theoretical predictions of future land performance and from this create foundation technical category maps to aid the decisions on appropriate repair and rebuild options.

Based on the geotechnical advice from Tonkin and Taylor, the Government announced on 26 June 2011 that properties in Christchurch and surrounding areas had been "zoned" into either of four zones, these being **Red**, **Orange**, **Green** and **White**. In summary, properties in the **Red** zone had been determined to be uneconomic and time-consuming to repair, or there was extensive land damage, or there was a high risk of damage from low levels of shaking, or the success of engineering solutions was uncertain and the only option was to retreat from the area. The **White** zone included the Port Hills where there was no liquefaction issue but where other considerations such as rock fall and slope stability were still to be addressed.
The **Green** zone was identified as the "go zone" where work could begin on the repair and rebuild of dwellings. There was expected to be a range of foundation solutions for this zone. The area identified as the **Orange** zone (between Green and Red zones) required more consideration but the future expectation was that properties in this zone would be re-classified as either Red or Green. A Government announcement was made on 28 October that 80% of the **Orange** zoned properties had been re-classified as **Green**. This means that at the time of writing there are approximately 130,000 properties in the **Green** zone. All of the **Green** zone is on the flat.

The remainder of this paper discusses the development of foundation solutions for the **Green** zone and issues with superstructure bracing repairs, which is particularly relevant for structures on the Port Hills. This information will be included in a new guidance document which is due to be published in late November 2011.

3.4 Categorisation of Properties in the Green zone

On 28 October 2011, Earthquake Recovery Minister Brownlee announced details of the sub-division of the Green zone into three Foundation Technical Categories (TC1, TC2 and TC3). The future liquefaction potential for these three technical categories has been determined from the process described above and is given in Table 1. Land in an un-categorised area will require engagement of a geotechnical engineer to determine the appropriate solution for the property, based on a site specific investigation.

It will be necessary to make site observations and conduct some site geotechnical investigation at each property before beginning a dwelling repair or rebuild. For TC1 and TC2 the geotechnical investigation will be a shallow investigation to determine the bearing capacity. A deep investigation will be required at TC3 properties. Processes are being put in place to ensure that the results of any investigations are input to a common database for future reference and some refinement of boundaries between the TCs may occur. It will not be possible for a TC to be upgraded (e.g. TC2 to TC1) for an individual property, but downgrades may occur.

3.5 New Foundation Solutions

For existing houses on the flat in Christchurch, there are generally three types of foundation. The first is an all-piled foundation where the dwelling is supported on either timber or concrete piles throughout (Type A). This was the style used in the early 20th century but was replaced by a concrete perimeter foundation with generally concrete piles inside the perimeter (Type B). Modern houses have employed a concrete slab on grade floor (Type C).

Given the future expectations of land settlement, the EAG has formulated house foundation designs for TC1 and TC2. One option is currently proposed for TC3 but other options are under development.

3.5.1 Dwellings in Technical Category 1

For new dwellings in TC1, as long as there is good ground[1] present then new dwellings may be lightweight construction on shallow piles with a timber floor or a reinforced concrete slab on grade may be used. NZS 3604 has allowed the use of unreinforced slabs but these were found to be vulnerable to settlement and ground spreading in the earthquakes. While the future expectations for the land do not involve these phenomena, it was considered good practice to reinforce new slabs.

Table 1 Expected future land performance

Foundation Technical Category	Future Land Performance Expectation from Liquefaction	Expected SLS land settlement(1) (mm)	Expected ULS land settlement(1) (mm)
TC1	Negligible land deformations expected in a future small to medium sized earthquake, and up to minor land deformations in a future moderate to large earthquake.	0 - 15	0 - 25
TC2	Minor land deformations possible in a future small to medium sized earthquake, and up to moderate land deformations in a future moderate to large earthquake.	0 - 50	0 - 100
TC3	Moderate land deformations possible in a future small to medium sized earthquake, and significant land deformations in a future moderate to large earthquake.	>50	>100

(1) Using recognised calculation methods such as the New Zealand Geotechnical Society Earthquake Engineering Practice Guidelines (NZGS, 2010)

[1] Good ground is defined in NZS 3604

(2) Note that the differential settlement would be expected to be approximately half the total settlement values listed above

3.5.2 Dwellings Technical Category 2

There was a need to ensure that foundations in TC2 could be either readily re-levelled or sufficiently stiff that they could span over reasonable areas of ground with lost support. While shallow piled foundations would deform under the potential future settlements, it was considered that re-levelling was a simple process of packing piles. However, an NZS 3604 reinforced concrete slab foundation would pose difficulties for re-levelling. Instead, a range of stiff foundation options has been proposed to ensure that the floor plate remains flat in the event of the potential ground settlements. Slight tilting of the floor plate may be expected but lifting methods are available for simple re-levelling should the expected limits be exceeded.

3.5.3 Dwellings in Technical Category 3

There is a high likelihood that future liquefaction in an ultimate limit state earthquake event in this TC will lead to ground settlements exceeding 100mm with differentials over the site exceeding 50mm. To guard against this eventuality, deep piles are considered to be an option, founded on solid bearing beneath the liquefiable layer. However, pile depths of approximately 10m are seen as the limit for an economical solution and there are areas of Christchurch where the liquefiable layer extends to greater depths. For this reason, alternative solutions will be necessary which, instead of relying on positive support from an underlying layer, can alter the geotechnical characteristics of the crust. Observations of combinations of dwelling performance and sub-surface conditions in the Canterbury earthquake series have shown that when there is a surface crust of around 2m to 3m the effects of liquefaction in the lower layers are significantly reduced. Options under consideration include containment of the soil beneath the foundation by piling around the perimeter of the building platform and improvement of the soil properties beneath the foundation by soil mixing or dynamic compaction. Any of these improvement methods would effectively create a TC2 condition, allowing dwelling foundation construction to proceed as outlined for TC2.

3.6 House Foundation Repairs

The EAG has suggested that the need to carry out house foundation repairs will be dependent on the “out of level” of the existing foundation and guidance has been provided on floor slopes and overall out of level to trigger either foundation repairs or rebuilds. These have been based on what have been considered to be acceptable tolerances in a number of standards and the NZ Building Code. For all house types, if a maximum slope between two points 2m or more apart is greater than 1 in 200 and the variation in floor level is greater than 50mm then this is considered to be a trigger for work to be undertaken on the foundation.

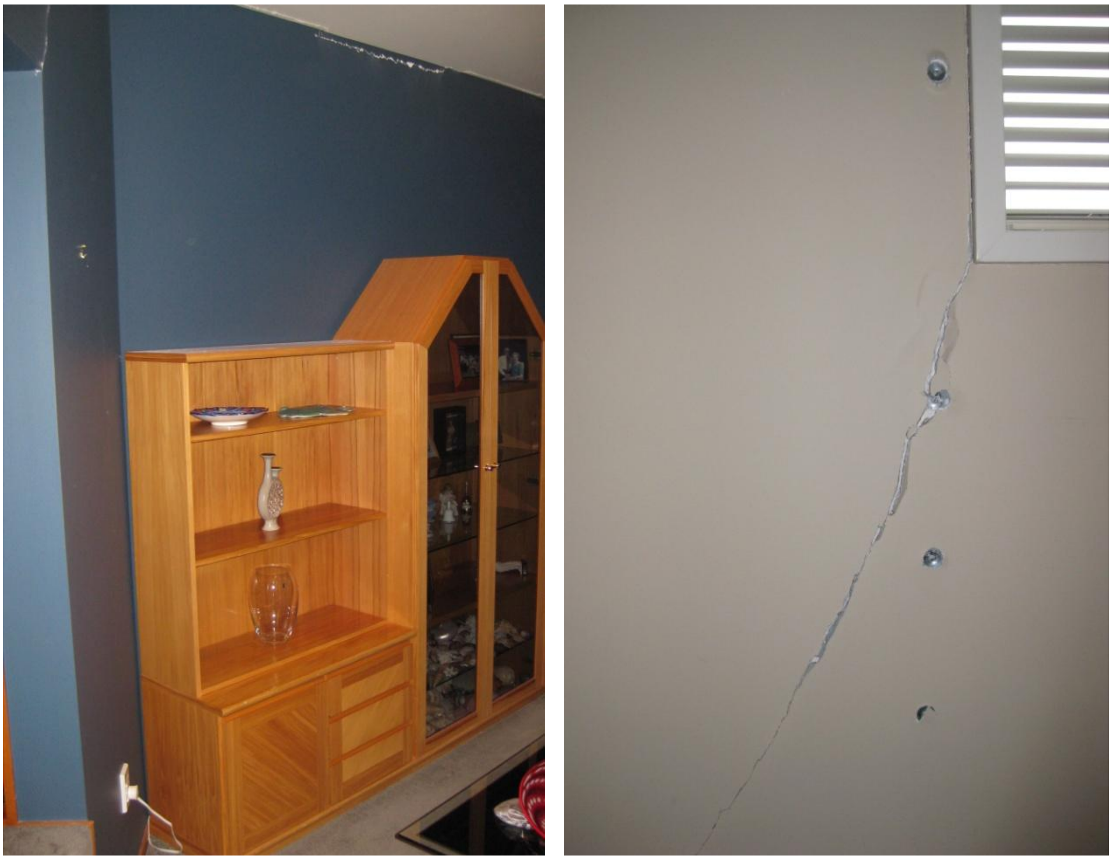
House foundation re-level/repair options have been developed only for houses in TC1 and TC2. Repair options will be dependent on the results of the shallow geotechnical investigation. For ground with an ultimate limit state (ULS) geotechnical bearing capacity of 300kPa or greater, repair of Type A dwelling foundations may be undertaken by packing piles. Sections of foundation wall may require replacement in Type B dwellings, in which case these will need to be reinforced to ensure that they are able to span a potential loss of support in the future. For Type C foundations, guidance is provided for re-levelling and crack repairs. If the geotechnical ULS bearing capacity is less than 300kPa a specific engineering design will be required.

It has not been possible to develop repair options for foundations in TC3 before the publication of the Guide. The results of trials of ground improvement methods will assist in the development of options, although a heavy geotechnical involvement can be expected for each individual dwelling.

3.7 Superstructure Bracing Repair Issues

From the point of view of the aim of the Building Code, typical houses behaved very well in the Canterbury earthquake series in that none collapsed, except in cases where the collapse initiation was rock fall or slope instability.

Sheet bracing materials also behaved well, providing stability to the houses while at the same time dissipating earthquake energy in a ductile fashion. In many houses, the visible damage to wall linings was minor (cracking of plasterboard joints - Figure 3(a)) while in others the damage was very significant (diagonal cracking through sheets and detached sheets - Figure 3(b)). In the second case, the repair solution is clear. The lining must be stripped off and replaced. The difficulty is in identifying the underlying damage in the first case and appropriately repairing the wall. In houses with minor damage throughout, the occupants have often commented that the house is “noisier” than it had been before the earthquakes. The reason for this is that in the earthquakes the fixings have moved small amounts in the lining, creating slots and under minor excitations from wind and aftershocks the house is able to flex more. There is no significant loss in strength because this is taken up once the fixings have reached the end of the slots.



(a) Minor cracking **(b) major damage**

Figure 3 Examples of plasterboard damage

Re-stopping the joints between sheets is not going to recover the dwelling stiffness. The EAG has therefore recommended that if the cracking is evident at the panel junctions and there is also evidence of movement at the skirting boards then the stopping should be scraped out and the panels re-fixed around the perimeter of the sheets. This has been shown by test to substantially regain the building stiffness.

4. CONCLUSIONS

This paper has provided a brief description of the damage sustained by the residential dwellings in Christchurch following the Canterbury earthquake series. It describes the setting up of an engineering advisory group by the DBH to provide repair and rebuild guidance for houses following the earthquake series. The procedure for determining the likely performance of the land in future earthquake events is discussed, leading to the sub-division of the Government announced Green Zone in three Technical Categories, each with proposed foundation repair or rebuild options. It is noted that options for technical category 3 are still being developed. Brief discussion of the issue of superstructure bracing and how it is expected to be addressed is also included. There are many other issues with respect to slope stability and retaining walls on hillside properties that have not been addressed in the paper. The damage is often unique to a particular property and so the development of guidance has been of a more general nature. Geotechnical and structural engineering input will be required for the repair of most damaged hillside foundations.

The Guide document published in December 2010 has been used extensively. The expectation is that the new Guide document, due to be published in late November 2012, will be used by the insurers, the project management offices (PMOs) coordinating repairs and rebuilds for the insurance companies and the Councils to ensure that the recovery of residential areas of Christchurch is undertaken in a manner appropriate to the expected future land behaviour and consistently across all repair and rebuild contractors.

ACKNOWLEGEMENTS

The author is the leader of the residential engineering advisory sub-group and is grateful to all the members of the EAG for the tremendous effort that they have put into the development of the Guide over the past 12 months.

REFERENCES

DBH (2010) Guidance on house repairs and reconstruction following the Canterbury earthquake. The Department of Building and Housing. Wellington, New Zealand. http://www.dbh.govt.nz/earthquake-reconstruction-guidance

SNZ (1999) NZS 3604 Timber Framed Structures, Standards New Zealand, Wellington, New Zealand.