Building in Resilience for Remediated Residential Housing

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ABSTRACT
The September 2010 Earthquake and February aftershock in Christchurch, New Zealand, resulted in extensive damage to residential buildings due to liquefaction and lateral spread. This paper describes some observations of the extent, severity and manifestation of the liquefaction and gives examples of typical damage to residential housing with regard to foundations. The paper then sets out planned measures for improved resilience to be incorporated into the rebuilding or remediation of damaged houses and design of new houses. Resilience in this context means not only minimising damage in future earthquakes but also improving the ability to reinstate or repair those buildings in liquefaction and lateral spread zones. The paper presents recommendations for revised foundation details and suggested design approaches.

Keywords: Liquefaction, remediation, resilience

1. INTRODUCTION

The city of Christchurch and the surrounding areas in Canterbury, New Zealand have recently been affected by a series of severe earthquakes and aftershocks.

On 4th September 2010, a magnitude M_w 7.1 earthquake occurred near Darfield, approximately 30 km west of the central business district (CBD). This triggered extensive liquefaction in areas of Christchurch and nearby towns. On 23rd February 2011, a magnitude M_w 6.2 earthquake occurred near Lyttelton, about 8 km south of the city and at shallow depth. Despite being of lesser magnitude, the resultant ground shaking was more severe in the city (PHGA = 0.9g recorded at some stations), resulting in significantly more extensive liquefaction. Two significant aftershocks with magnitudes M_w 5.6 and M_w 6.0 occurred on 13th June 2011, causing re-liquefaction in many areas. In addition to these major events, a large number of aftershocks have occurred, centred in the same general areas.

The liquefaction caused extensive damage to land and buildings, particularly in the residential areas. After each event, teams of Geotechnical & Civil Engineers carried out detailed inspections and assessments of the liquefaction related land and building damage.

The purpose of this paper is to describe the nature and severity of this damage with regard to the residential properties, and to propose measures that could be implemented in future for construction of new buildings in affected areas (and other similar situations) to improve resilience for future events.

Damage to residential property also occurred due to ground shaking, rockfall and landslips, but this paper focuses only on liquefaction-related issues and measures to improve resilience in domestic structures.

1.1. Types of housing

This paper is concerned with the particular type of housing that is prevalent in New Zealand. Because New Zealand is an earthquake prone country, with a low density population, residential houses tend to be timber-framed, low-rise (1-2 storey) and on individual plots (i.e. generally stand-alone detached buildings). Double-skin brick clad dwellings are uncommon in New Zealand with the majority of the dwellings being clad in bricks, or timber weatherboards. In Christchurch the majority of the older building stock (pre 1970's) was generally constructed with timber floors while the majority of dwellings constructed post 1980 have concrete floors. Figure 1 illustrates the three general types of foundations common in the Christchurch residential suburbs.

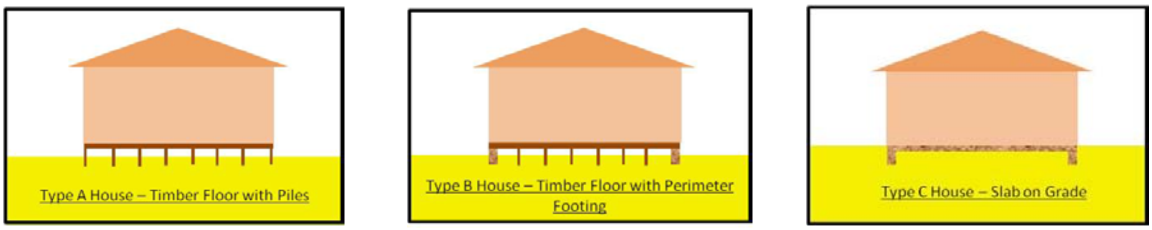


Figure 1. Prevalent building foundation types

It is a quirk of the New Zealand building industry that house "piles" are short, low-penetration timber piles that hold up the building frame and floor, as illustrated in Figure 1. In this context, these "house piles" need to be differentiated from foundation "deep piles" that are more familiar to foundation engineers.

2. LAND DAMAGE

Most of Christchurch occupies a flood plain, with deep deposits of alluvial/fluvial origin. For much of the area (particularly in the east of the city), the near-surface soils comprise liquefiable sands and silts, and the land is low-lying with meandering rivers. The liquefaction that occurred has been well documented (Geotechnical Land Damage Assessment Reports – T&T 2010a and T&T 2010b). Damage to land was manifest in several ways, including lateral spread near waterways, sand ejection and ground cracking due to phenomena other than lateral spread (e.g. oscillation damage) and variable settlement. Figure 2 shows examples of these effects.

Figure 2. Examples of land and building damage

Following each event, a regional reconnaissance damage mapping exercise was undertaken by geotechnical engineers on behalf of the state insurance organisation the Earthquake Commission (EQC). Areas of severe land damage were identified and then further detailed local mapping was undertaken. The land damage was categorised in terms of the criteria given in Table 1, which summarises the effects of observed liquefaction on land.

Table 1. Land damage categories and performance levels

Category	Description	Level
Very severe	• Extensive lateral spreading (>1 m) • Surface rupture, large open cracks, (>100 mm) • Extensive liquefaction (ejected sand) • Significant horizontal and vertical displacement >200 mm • Heavy structural damage to buildings • Dislocation of roads/services • Affected dwellings are beyond economic repair and likely to be uninhabitable	L5
Major	• Extensive liquefaction (ejected sand) • Large cracks from ground oscillations • Horizontal and vertical displacement >50 mm • Structural damage to buildings • Major differential settlement >1/100 • Damage to roads and failure of services • Affected dwellings are beyond economic repair and likely to be uninhabitable or habitable in the short term	L4
Moderate	• Visible signs of liquefaction (ejected sand) • Small cracks from ground oscillations (<50 mm) • No vertical displacement of cracks • Some structural damage to buildings • Moderate differential settlement <1/100 • Moderate damage for roads/services • The majority of houses are likely to be habitable in medium term with reduced serviceability	L2 to L3
Minor	• Shaking-induced damage – cyclic deformation • Minor ground cracking (tension) and buckling (compression) • No signs of liquefaction visible at the surface • No permanent horizontal or vertical displacements • Occasional minor structural damage and varying degrees of cosmetic damage • Minor street, pavement and landscaping repairs required	L0 to L3
Building only	• No apparent land damage • No signs of liquefaction visible at the surface	L0

Figure 3 illustrates how the observed land damage generally related to topographic features.

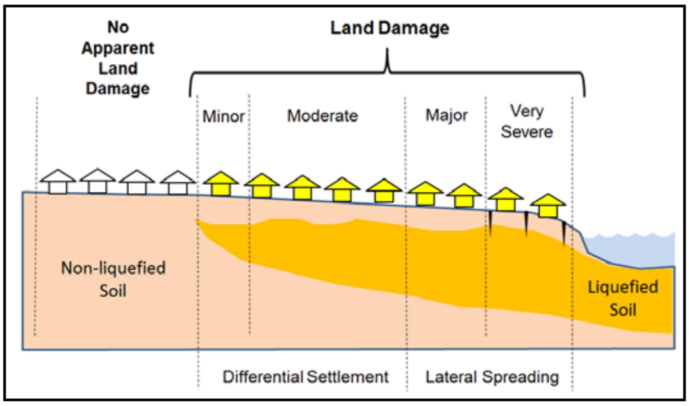


Figure 3. Land damage relationship to topography

3. BUILDING DAMAGE

The land damage described above caused consequent damage to buildings. To be able to plan measures for building in resilience to structures from future earthquakes (i.e. to tolerate land movement) it is necessary to understand: the types of buildings in the affected areas, the types of building damage that occurred and how these were caused.

Building damage can be divided into two broad categories: damage that was caused solely by earthquake shaking; and damage that resulted from ground deformation including liquefaction, lateral spreading or landslip.

While shaking damage to dwellings has been observed on the areas of flat land in Christchurch, the February and June 2011 events in particular caused significant shaking damage to hillside houses. The observed high vertical accelerations (measured at up to 2.0g) were responsible for severe damage to tile roofs and brick veneers, and unreinforced foundations were often severely cracked. However, this paper is focused on the geotechnical related damage resulting from ground distortions in the liquefiable zones on the Christchurch plains.

Liquefaction-induced ground movement has caused stretching, hogging, dishing, racking/twisting, tilt, differential settlement, differential displacement or any combination of the above to residential buildings. The severity of the damage is dependent on the damage type, the type of building damaged, the building geometry and the amount of foundation movement that has occurred.

Figures 4(a, b & c) summarises the types of building damage that were observed and need to be protected against from future earthquake events.

Uniform Settlement	**Tilt Settlement**
	
For uniform settlement the complete foundation has settled by the same amount over the area of the foundation.	With tilt settlement, the whole foundation tilts as a rigid body.

Figure 4(a). Simple settlement cases

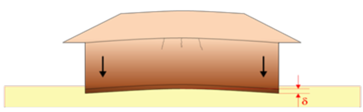
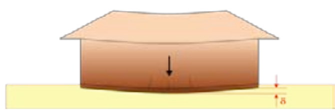
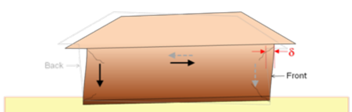
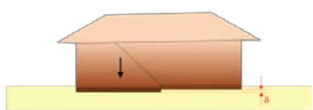
Hogging	**Sagging or Dishing**
	
Racking/Twisting	**Differential Settlement – Abrupt Change**
	
Twisting of the foundation can occur where all corners of the foundation have settled by different amounts.	

Figure 4(b). Differential settlement cases

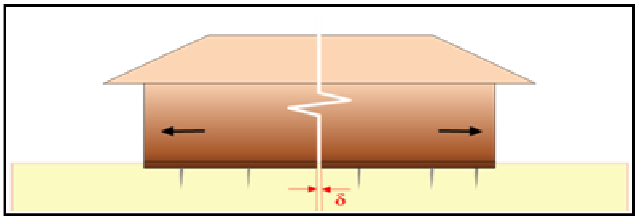


Figure 4(c). Lateral stretching

4. REMEDIATION POLICY AND PROCESS

4.1. Significant factors

Extensive work has been carried out to enable a construction/re-construction policy to be prepared for those areas affected by liquefaction in Christchurch. This included detailed data gathering of the type and severity of both land damage and building damage, analysis of cause-effect relationships, and discussions with government, local government, insurance companies, designers and builders. The following factors proved significant:

- Vertical settlements were generally not well predicted using conventional re-consolidation theory, probably due to the ejection of sand. In areas where sand was ejected vertical settlements were generally greater than those expected while settlements were generally lower than expected in areas where sand was not ejected.
- Differential settlements were more severe than would be expected from re-consolidation of liquefied layers, also due to localised sand ejection.
- Lateral spreading movements occurred in some places greater than 200 m from watercourses.
- Many of the existing houses did not have tensile reinforcement in the footings (Type B housing) or floor slab (Type C housing). This resulted in stretching of the building due to lateral ground spreading.
- Type A houses (short house piles) tended to suffer severe foundation distortion but were relatively easy to repair because of the ability to re-level the structure. Conversely, the Type C houses suffered little distortion if the slabs were stiff and able to resist tension but were otherwise very difficult to repair (the majority of Type C houses had no tensile reinforcement, or had non-ductile reinforcement in the slabs). Type B houses were somewhere in between in practicality of repair.
- Damage severity was clearly related to the "crust thickness" (i.e. the surface non-liquefiable layer) and the total depth of liquefaction. However, the criteria set out by Ishihara (1985) for "manifestation" of liquefaction effects at the ground surface proved to be of limited help in differentiating levels of damage, and hence providing criteria for building in resilience to future housing. A new index, termed the "Liquefaction Severity Number" (LSN) has been proposed by other authors and this tends to show a much more useful correlation with damage levels. This index will be discussed in a paper under preparation, with the correlations presented in detail but can be simply defined as:

  "The integration from the ground surface to the full depth of theoretical liquefaction of induced volumetric strain divided by the depth to that strain."

  Clearly this biases the effects of liquefaction to the near surface occurrences, and provides for the benefit of crust thickness.

Taking account of these factors, the following philosophy has been adopted by the Department of Building and Housing (DBH) for the repair and reconstruction of dwellings:

- Negligible effects of liquefaction under the serviceability limit state (SLS) design level. This level is set in the code of practice at AEP 1:25. Damage should be no more than minor, and readily repairable.
- Life safety maintained (i.e. no collapse/fire) under ultimate limit state (ULS) design level. This level is defined in the code of practice at AEP 1:500 for normal residential housing.
- Improved performances under ULS such that temporary occupancy can be safely maintained following a design event and/or repairs can be affected cheaply and quickly.

4.2. Implementation of remediation policy

For rapid implementation of repairs it was first necessary to "zone" the entire area of greater Christchurch as follows:

- Red Zone: Land that has been shown to be most susceptible to severe damage in recent events. Considered by Government and the appointed recovery agency (Canterbury Earthquake Recovery Authority – CERA) to be impractical, uneconomic and too disruptive to re-habilitate. Ground remedial work would require large scale engineering measures and the demolition of whole suburbs.

- Orange Zone: Intermediate zone for which further engineering and economic analysis would require more time to determine whether the area should be rezoned red or green.

- Green Zone: The area for which land remediation and house re-building or new building could commence with appropriate engineering input.

The Green Zone, however, required further sub-division on the basis of low, medium and high probability of future liquefaction. This was done by DBH primarily on the basis of observations from the various earthquake/aftershock events but also with the aid of sub-surface data from a series of detailed investigations throughout the affected suburbs. These divisions of the Green Zone required different technical foundation solutions and hence have been termed Technical Categories (TC1, TC2 and TC3). These are defined in Table 2 and shown on Figure 5.

Table 2. Observed land performance and proposed technical categories

Foundation technical category	Observed land performance
TC1	TC1 covers those areas of greater Christchurch where no significant land deformation occurred as a result of liquefaction from either the 4 September 2010 earthquake or the 22 February 2011 aftershock and there is generally greater than 3 m depth to groundwater.
TC2	TC2 covers those areas of greater Christchurch where no or negligible land deformation occurred as a result of liquefaction from the 4 September 2010 earthquake and only small amounts of land deformations occurred as a result of the 22 February 2011 aftershock. It also includes some areas that did not suffer land damage but are considered at some risk of potential ground damage from liquefaction until proved otherwise.
TC3	TC3 covers those areas of greater Christchurch where land deformation occurred as a result of liquefaction from the 4 September 2010 earthquake and moderate to severe land deformations occurred as a result of or the 22 February 2011 aftershock, together with the areas identified at high future probability of ground damage.
Un-categorised	Un-categorised areas include: parks, commercial areas and properties greater than 4,000 m^2, together with those areas that were not mapped for damage from the 4 September 2010 or the 22 February 2011 earthquakes.

Detailed guidelines for the repair and re-building of dwellings in these technical categories has been prepared by a diverse working group of Engineers, designers and builders who formed an Engineering Advisory Group (EAG) appointed by the Department of Building & Housing. The EAG published guidance documents on the repair & reconstruction of residential dwellings following the Canterbury

Earthquakes in three versions (refer www.dbh.govt.nz/canterbury-earthquake-residential-building).

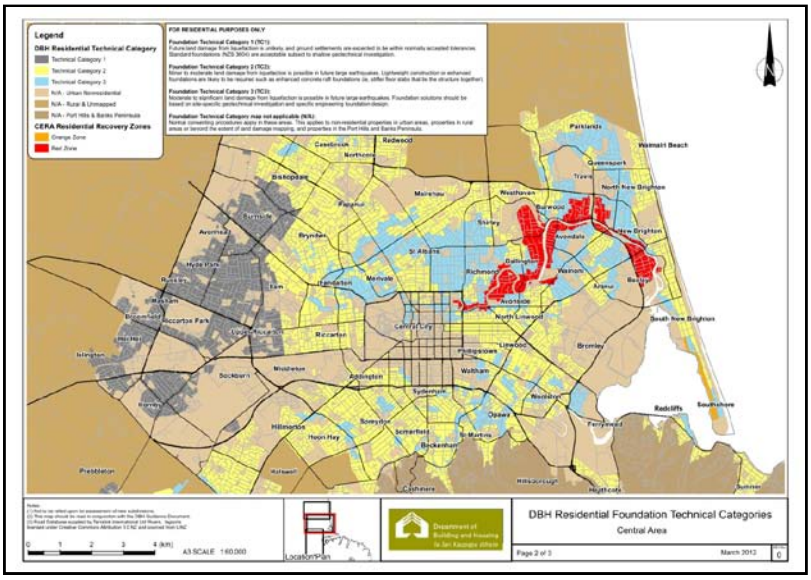


Figure 5. DBH Technical Category map of central Christchurch

The overall philosophy adopted by the Engineering Advisory Group (EAG) for rebuilding in areas prone to liquefaction was:

1. Where possible, structures should be easily repairable
2. Light structures are preferable to heavy structures (for shallow foundations)
3. Floor systems should be either flexible (and easily repairable) or stiff (and easily re-levelled)
4. Foundation systems that are not easily repairable (i.e. deep piles) should be designed to provide a greater level of protection than those that can be easily repaired or re-levelled.
5. Regular structure shapes are preferable to more complex shapes.
6. Prevent penetration of the non-liquefiable crust where possible.

Space does not permit a detailed presentation of the guidelines. In summary, the principles behind the guidelines are given in Table 3.

Table 3. General repair or re-build strategies

Building type	TC1	TC2	TC3
Type A	Re-level and re-pile if required. No enhancement required.	As for TC1. New build.	Special engineering measures required – see section 5.
Type B	Re-construct portion of perimeter wall in accordance with current code, re-pile under house.	As for TC1 but with enhancement perimeter wall throughout.	Special engineering measures required – see section 5.
Type C	Repair slab where practical For new dwellings concrete slab with nominal mesh reinforcement sufficient.	Localised repair of floor with enhanced tensile and flexural strength permissible For new dwellings stiff heavily reinforced concrete slab required.	Special engineering measures required – see section 5.

4.3. Special measures for TC3

If a property is within a TC3 area, the implication is that moderate to severe land damage has likely already occurred or is likely to occur in future events. The principle here would be to demolish part or all of the moderately to severely damaged dwellings and construct new dwellings with enhanced special foundations that are more resilient. Dwellings with minor to moderate damage can be repaired particularly if weight is removed from the structure (i.e. remove heavy roof or cladding).

Three broad types of foundations for new dwellings have been adopted to accommodate or resist the settlement and lateral spreading ground movements associated with TC3, namely:

- Deep piles
- Site ground improvement
- Surface features and shallow foundations.

Table 4 summarises the constraints relating to these options.

Table 4. Overview of proposed TC3 foundation types

Type	Objectives	Dwelling Constraints	Land Constraints
Deep piles	Negligible settlement in both small and larger earthquakes	No height and/or material constraints likely	Not suitable where either major or severe global lateral movement likely or dense non-liquefiable bearing layer not present
Site Ground Improvement	Improving the ground to receive a TC2 foundation	Limits on some two storey/ heavy wall types and plan configurations	Some ground improvements can be specified to accommodate major lateral stretch
Surface structures/ shallow foundations	Repairable damage in future moderate events	Only suitable for light construction, regular in plan	Standard option, suitable for minor to moderate lateral stretch and vertical settlement, or Specific design concepts designed for major lateral stretch and some for potentially significant vertical settlement

4.4. Deep piles

The objective of using deep piles is to obtain dependable vertical load capacity at both SLS and ULS levels of earthquake. Deep piles are not considered suitable for severe lateral spreading situations, and require careful detailing for ductility to accommodate lesser levels of lateral spreading.

The following general requirements are necessary for a site to be considered suitable for deep pile foundations in TC3:

1. There must be a clearly identifiable bearing stratum that will not liquefy and that will provide adequate support for the pile type being considered. (For example, dense sand or gravel with corrected SPT $N_{60} > 25$ or CPT $q_c > 15$ MPa).
2. There must be confidence that the bearing stratum is sufficiently thick to provide adequate support for the piles and to bridge over any underlying liquefiable layers.
3. The bearing stratum must be extensive enough across the site to provide uniform support to the entire footprint of the dwelling.
4. The piles must be capable of transferring the weight of the building to the bearing stratum, reliably, and meeting settlement requirements, even with liquefaction of overlying soils, and including effects of down-drag from non-liquefied crust.
5. Pile foundations should be capable of withstanding lateral movement at the ground surface relative to the bearing stratum without suffering a brittle shear failure. A minimum lateral movement of 200 mm should be considered even for sites with no surface evidence of lateral movement.

6. Pile foundations are not considered suitable (without special engineering) for sites where major or severe global lateral movement (>300 mm) has occurred.

4.5. Site ground improvement

There are a number of ground improvement methods available for mitigation of the effects of liquefaction-induced by seismic shaking. In 2011 the Department of Building and Housing commissioned a field trial of a number of ground improvement options. During the field trial the selected options were subjected to simulated ULS levels of shaking, and the performance of each of the mitigation methods was assessed by reference to measured settlements, ground vibration and pore pressure response. The results of these tests can be accessed on the following website: https://canterburyrecovery.projectorbit.com/Shared/QE2%20Trial.pdf.

It is intended that ground improvement carried out following these guidelines will allow the construction of either concrete or timber floors that are supported on foundations that meet the requirements of TC2.

The following is a list of the five types of ground improvement solutions that have initially been recommended:

- Densification of either the crust layer by: excavation and replacement/re-compaction, dynamic compaction (DC), or rapid impact compaction
- Crust strengthening/stabilisation by: excavation, stabilisation mixing & replacement or in-situ stabilisation (via Panel mixer or rotary cutter machine)
- Deep soil mixing
- Stone columns
- Low mobility grout.

4.6. Surface structures

The objective of the surface structures was to provide surface foundation options that are readily repairable or able to be re-levelled in the event of future differential settlements and lateral ground movements. Some of the options are expected to be able to accommodate a significant degree of lateral spreading without causing rupture of the superstructure. The surface structures are intended to be constructed essentially directly on the ground, that is without ground improvement or deep foundation works.

The options fall into two groups:

(a) Lightweight platform: Capable of accommodating minor/moderate differential settlement and or lateral strain. Lightweight enables re-levelling (e.g. pressure grout/foam).

(b) Stiff underside platform: Capable of accommodating major lateral strain and "smooth-out" severe differential ground settlements. Ground may slide under platform or carry platform with it such that ground cracks from around or under platform.

(c) Concepts for specific design: Capable of accommodating major lateral strain and significant vertical settlement but requiring further detailed Engineering design.

Example concepts include:

- Isolated short piles beneath stiff continuous bearers: provides for sliding for lateral spreading and re-levelling for severe differential settlement

- Timber "house piles" bearing on reinforced concrete under-slab and reinforced gravel raft: provides the best features of Type A house and Type C house (see Figure 1). Resists lateral spread and easy to re-level.

- Isolated concrete pads beneath stiff continuous bearers or Steel beams orthogonally over pre-stressed concrete ground beams with ground beams aligned in direction of expected lateral spread. As above for sliding and re-levelling.

5. CONCLUSIONS

Extensive damage has occurred to residential buildings in and near Christchurch as a result of the series of 2010-2011 earthquakes and aftershocks. Much of the damage to buildings was related to land damage due to liquefaction.

This paper describes the extent, severity and type of damage and develops the philosophy for remediating, rebuilding or new building in relation to future events:

- Negligible (readily repairable) damage from liquefaction under SLS
- Maintain life safety under ULS
- Enhanced performance under future ULS events such that temporary occupancy can be safely maintained and/or repairs can be affected cheaply and quickly.

The paper sets out how the land has been categorised for repair/rebuild options and summarises some of these options, with special emphasis on the most demanding damage category (termed TC3). Some design consideration for deep piles, ground improvement and special surface structures with shallow foundations are described.

ACKNOWLEDGEMENT
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