EQC
EARTHQUAKE COMMISSION
Komihana Ruwhenua

Residential Ground Improvement

Findings from trials to manage liquefaction vulnerability

Acknowledgements

The Earthquake Commission gratefully acknowledges the collaboration and support of the following organisations:

- The National Science Foundation (USA)
- The US Network for Earthquake Engineering Simulation
- The University of Canterbury
- The University of Texas (at Austin, USA)
- Oregon State University (Corvallis USA)
- Brigham Young University (Provo Utah, USA)
- The Department of the Prime Minister and Cabinet
- The Ministry of Business, Innovation and Employment
- Housing New Zealand Corporation
- The New Zealand Transport Agency
- The Insurance Council of New Zealand
- AA Insurance
- IAG Insurance
- Lumley General Insurance Limited
- Southern Response
- Tower Insurance
- Vero Insurance.

The Earthquake Commission especially thanks its engineering partners, Tonkin + Taylor, and all of the consultants, contractors and sub-contractors who have contributed in some way to this report, in particular Dr Sjoerd Van Ballegooy, Kate Williams, Tony Fairclough, Richard Phillips, Rob Hunter, Trevor Coe, Miles Stretton, Terry Wynyard and John Walsh.

Finally, the Earthquake Commission acknowledges with gratitude to the homeowners of all the properties involved in the Pilot. Their support has enabled the development of practical and more affordable ground improvement methods that will enhance resilience to future earthquakes in New Zealand and elsewhere which will mitigate the social and economic impact of future earthquakes.

Tonkin+Taylor

PREPARED BY:
TONKIN + TAYLOR AND THE EARTHQUAKE COMMISSION

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Foreword

The Canterbury earthquakes of 2010-2011 have highlighted the earthquake problem as fundamentally one of risk management. Ideally, this is achieved by 'avoiding' building in areas most vulnerable, using urban planning, and the 'control' of expected performance in areas of lower vulnerability through proven construction practices. The 'transfer' of residual risks through insurance is intended to ensure adequate financial indemnity if there is a disaster. The sheer scale of the damage to Canterbury residential property from the earthquakes shows that a reliance on risk-transfer without mitigation actions is unlikely to meet community expectations of resilience in their buildings and land.

Looking back, large shallow earthquakes struck New Zealand repeatedly in the 1930s and early 1940s, prompting the introduction of principles for seismic design, developed largely in Japan and California. These were the basis of our first national building code in 1935. Reconstruction financing was another early consideration with the forerunner of the Earthquake Commission (EQC) created during the 1940s as a way to protect people's property through insurance.

Few in the New Zealand community today, however, had experience of a large destructive event prior to the recent Canterbury earthquakes and the consequential losses. Destructive urban earthquakes are rare but awareness of the strategic gains in resilience that followed those historic experiences provided the impetus for the work in this report.

Some research is best done locally, because the knowledge needs are unique – no one else will do it – and it provides essential support to important sectors of the economy and society. The practical lessons learned in increasing the resilience of residential housing on land that is vulnerable to liquefaction in Canterbury is no exception. In undertaking this ground improvement research EQC, together with Tonkin + Taylor (T+T), facilitated the involvement of some of the world's leading experts on liquefaction, and the collaborative efforts of many organisations, including the University of Canterbury, the Ministry of Business, Innovation and Employment (MBIE), Housing New Zealand Corporation, the New Zealand Transport Agency (NZTA), the University of Texas at Austin, (USA), Oregon State University (Corvallis, USA), Brigham Young University (Provo, Utah, USA), the US National Science Foundation, and the US Network for Earthquake Engineering Simulation.

The application of the lessons from these investigations also would not have been possible without the trust and collaborative problem-solving of homeowners and their insurers, local authority consenting officers, engineers and contractors. To appreciate the significance of trends and technologies elsewhere, and to evaluate their relevance and priority for potential use and further local involvement, are important in planning outcomes for commerce and government and critical to New Zealand's long-term resilience to natural hazards.

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Executive summary

The Canterbury Earthquake Sequence (CES) 2010-2011 triggered widespread liquefaction. In some areas this resulted in consequential land and building damage.

The Ground Improvement Programme (GIP) is a research project that informs appropriate integrated solutions for building houses on land vulnerable to liquefaction. It has been co-ordinated by Tonkin + Taylor (T+T) for the Earthquake Commission (EQC) with assistance from leading experts from New Zealand and around the world.

The GIP was developed to identify shallow ground improvement methods that can be applied on existing residential suburbs to stiffen, strengthen and/or thicken the near-surface soil crust.

The GIP included:

- A comprehensive set of testing trials (referred to as the Science Trials)
- A Pilot Project applying ground improvements (which performed well in the Science Trials) on 31 existing residential properties.

The GIP has identified, developed and trialled practical and affordable shallow ground improvement methods able to be used on cleared sites to mitigate the potential for liquefaction from building damage associated with building houses on land vulnerable to liquefaction. Land with a suitably strengthened, engineered non-liquefying crust will mean houses can be built with affordable improved levels of resilience in future earthquakes and the damaging effects of liquefaction from the underlying soils will be reduced.

The Science Trials considered seven existing ground improvement methods for cleared properties where houses will be rebuilt. In addition, a new ground improvement method was developed for use under existing repairable houses (i.e. where the houses can remain in-situ).

The Science Trials tested how well various ground improvement methods worked when the underlying soil layers are liquefied. The data showed that differential ground surface settlement (which causes damage to houses when the underlying soil liquefies during earthquakes) can be appropriately controlled by construction of shallow ground improvement works.

These trials also helped to develop reliable, practical and affordable testing methods to rapidly verify that the ground improvement methods work in future earthquakes, i.e. the non-liquefying crust strength and stiffness to ensure good performance is achieved.

The Pilot Project (the Pilot) set objectives to verify the practicalities and costs of constructing ground improvement methods that had performed well in the Science Trials on existing residential properties. Five main types of ground improvement were constructed on 31 residential properties in TC3 categorised land in Christchurch and Kaiapoi to assess real-world application. This Pilot has been used to enhance the understanding of those involved in the methods of the ground improvement and the processes, including selection, design, consenting, procurement, construction and verification of the ground improvement process. Results from the GIP have made a key contribution to the 2015 update of the MBIE guidance for repairing and rebuilding houses on TC3 land in Canterbury.

The GIP and subsequent changes to regulatory guidance have provided more affordable ground improvement options for building or rebuilding houses on residential land in Canterbury vulnerable to liquefaction and opened up the residential ground improvement market to smaller, non-specialised contractors. Contractors have upskilled to enable them to carry out a wider range of ground improvement methods.

For houses of 146m^2, as per MBIE guidance, four methods of ground improvement for cleared sites can be constructed costing approximately $36,000 - $73,000 (excl GST), which will enable lower cost foundations to be used on the enhanced land.

A new experimental method of ground improvement, Horizontal Soil Mixed (HSM) beams that can be constructed beneath some existing and repairable houses, costing approximately $110,000 - $140,000 (excl GST). The HSM beams will reduce the vulnerability of the land but not to the same extent as cleared site ground improvement methods.

The results from the GIP are useful to property owners, engineers, builders and property developers, private insurance companies, local authorities and central Government agencies building or rebuilding houses on land vulnerable to liquefaction across New Zealand and the world.

1 Introduction

This report summarises the lessons from the Earthquake Commission (EQC) Ground Improvement Programme (GIP) co-ordinated by Tonkin + Taylor (T+T) for EQC with assistance from University of Texas at Austin, Oregon State University and Brigham Young University Utah.

The Canterbury Earthquake Sequence (CES) of 2010-2011 included four significant earthquakes that triggered widespread liquefaction and land damage varying in severity throughout the region. The majority of areas affected by severe liquefaction-induced land damage generally coincided with lower lying areas where there were layers of liquefying soils and where the groundwater is closer to the ground surface and hence has a relatively thin non-liquefying crust layer.

Liquefaction triggering occurs when earthquake shaking is strong enough for excess pore water pressure to build up, resulting in a full loss of strength of the soils. In some areas, liquefaction triggering affects a significant portion of the soil profile, resulting in consequential effects at the ground surface. In other areas liquefaction triggering occurs in isolated soil layers deep below the ground surface, with no consequential effects at the ground surface. The primary consequential effects, and hence vulnerability from liquefaction at the ground surface, are total settlement, differential settlement, ejected sand, topographic re-levelling and lateral spreading.

For the purposes of this report liquefaction vulnerability refers to the vulnerability of residential land to liquefaction related land and buidling damage in a future earthquake.

The GIP was undertaken to identify practical ground improvement methods that could be used to stiffen and/or thicken the near-surface soil crust on residential properties. The aim was to find affordable ways to create building platforms less vulnerable to liquefaction damage in future earthquakes. A stiff or thick non-liquefying soil crust enables lower cost foundation systems that meet the New Zealand Building Code and provide greater resilience than sole reliance on stiffened foundation systems.

The GIP used a collaborative approach to foster understanding of the research objectives among diverse groups and interests in the Canterbury community, and to facilitate acceptance and application of ground improvement where most relevant.

The GIP was divided into two main work streams:

- The Ground Improvement Trials – 'the Science Trials'
- The Ground Improvement Pilot Project – 'the Pilot'.

The Science Trials included simulated earthquake testing of various ground improvement panels. Using results from the Science Trials MBIE updated its 2012 guidance document *Repairing and rebuilding houses affected by the Canterbury earthquakes,*[1] in April 2015.[2,3]

The Pilot involved the 'full scale' construction of various shallow ground improvement solutions on residential properties. This will help improve understanding and education of ground improvement on residential properties, as well as determining the most practical and affordable solutions, given constraints such as construction access, vibration and noise. The relationship between the two elements of the GIP and MBIE's guidance and how they both inform the application of ground improvement is summarised in Figure 1.1.

[1] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Version 3, December 2012.

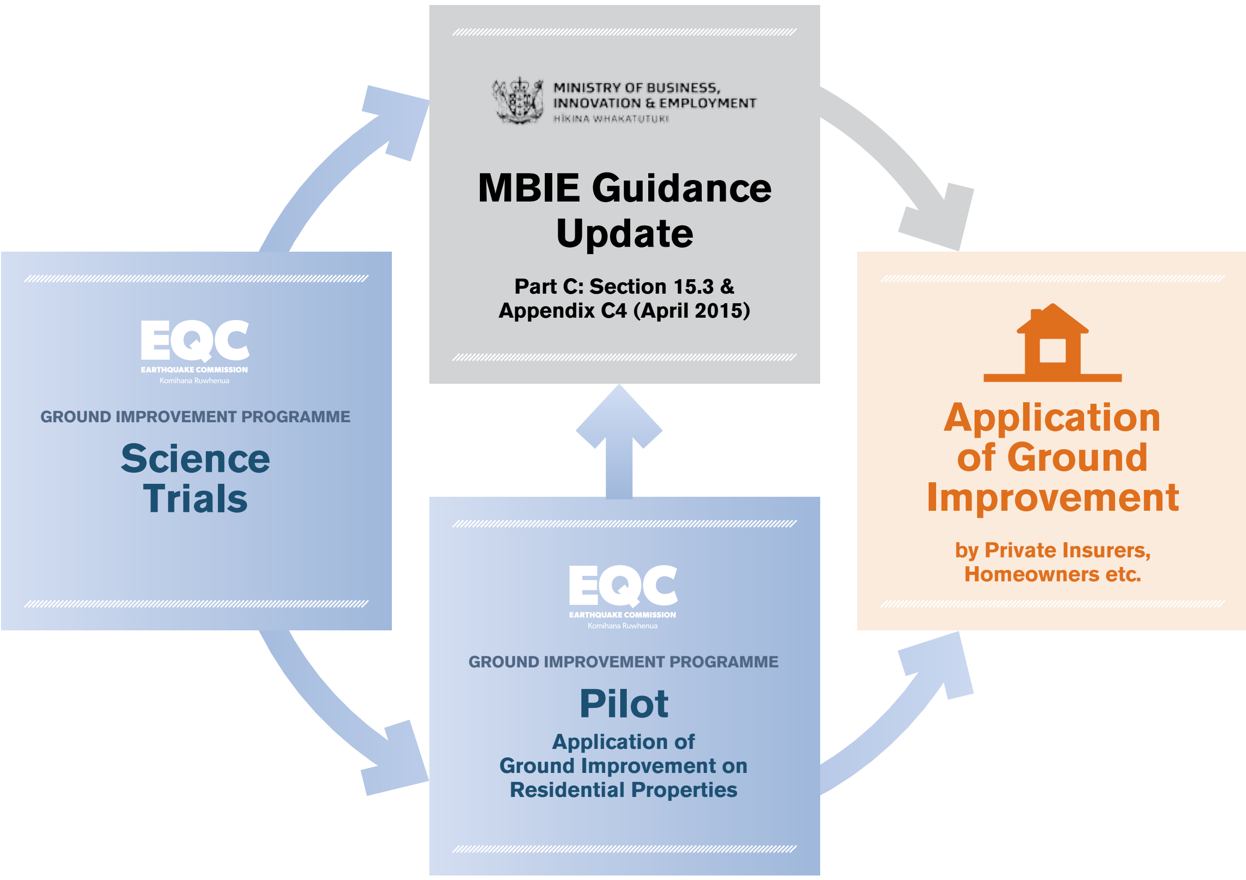
[2] MBIE guidance document, Section 15.3 update, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Version 3a, April 2015.

[3] MBIE guidance document, Appendix C4 update, *Repairing and rebuilding houses affected by the Canterbury earthquakes*, Version 3a, April 2015.

This report is for anyone with an interest in the application of ground improvement for residential properties vulnerable to liquefaction. While the 'lessons' in this report are based on work undertaken in Canterbury, New Zealand, it has relevance to other buildings on soils vulnerable to liquefaction, both nationally and internationally. This information is not intended to form a complete technical report on the GIP undertaken in Canterbury.

This report is a summary of the results, lessons and outcomes from the GIP. For more information on the methods, consents and specifications see Appendix A.

Figure 1.1 Relationship between the GIP and MBIE guidance



2 Purpose

Following the CES, damage caused by liquefaction could be seen throughout Christchurch and parts of the Selwyn and Waimakariri districts. The CES caused ground surface subsidence in many areas and for some properties meant an increase in vulnerability to liquefaction-related damage in future earthquakes. Liquefaction-induced damage[4] affected approximately 51,000 of the 140,000 urban residential properties in Canterbury and caused approximately 15,000 homes to be damaged beyond economic repair.

Prior to the CES, ground improvement for liquefaction mitigation was seldom done on residential land in New Zealand. This was partly owing to the relatively high construction costs for ground improvement compared to the value of the homes that would be built on the land.

Ground performance across a range of ground conditions throughout Canterbury was seen during the CES. Generally, in areas with liquefying soils, residential homes founded on thicker and stiffer non-liquefying crusts were observed to perform better than residential homes with thinner or less stiff non-liquefying crusts. The GIP was instrumental in collating scientific data to support and test this.

Ground improvement typically involves treating the soil by either: compacting it to make it denser; densifying and reinforcing the soil with columns of dense stone aggregate or timber poles; stabilising the soil by mixing in cement; or replacing the soil with non-liquefiable material, such as gravels. Once the ground has been suitably improved and has an effective non-liquefying crust, a house can be built using a more cost-effective foundation system than previously available.

The GIP was carried out to facilitate research and education to increase New Zealand's resilience to natural disasters. The GIP sought to enable and promote a more holistic approach to building (and repairing) homes on liquefaction-vulnerable land.

Although the GIP was led by EQC it was also funded by other parties, including MBIE, Housing New Zealand, the Network of Earthquake Engineering Simulation (NEES) in the United States of America (USA), and the National Science Foundation (NSF) in the USA.

The Science Trials portion of the GIP work was peer reviewed by leading national and international experts from the University of Canterbury, Cornell University (USA), University of California Berkeley and University of California Davis (USA). The lessons from this work can be used throughout New Zealand and the world for residential properties vulnerable to liquefaction from earthquake shaking.

The Pilot portion of the GIP was conducted in collaboration with insurance companies to ensure the practicalities of designing, consenting and constructing the proposed ground improvement works would be understood, providing a better outcome for all parties at all stages of the process.

KEY POINTS

Purpose

1. **The EQC GIP was instrumental in identifying, developing and trialling practical and affordable ground improvement methods for use on cleared sites to mitigate the risks of building on residential land vulnerable to liquefaction.**
2. **Residential land with a suitably strengthened engineered non-liquefying crust will enable houses to be built with affordable, improved levels of resilience in future earthquakes and reduce the damaging effects of liquefaction from the underlying soils.**

[4] Russell, J., van Ballegooy, S., Rogers, N., Lacrosse, V., Jacka, M. *The effect of subsidence on liquefaction vulnerability following the 2010 – 2011 Canterbury Earthquake Sequence*. Proceedings of the 12th Australia New Zealand Conference on Geomechanics, 2015, pp. 610-617.

3 Background and Programme

3.1 Liquefaction vulnerability

For the purposes of this report liquefaction vulnerability refers to the vulnerability of residential land to liquefaction-related land and building damage in future earthquakes.

The geology of Canterbury is characterised by sand, silt and gravel on a flat coastal plain. The resulting near-surface loose sand and silt have a high potential for liquefaction. Some areas of Canterbury have always been vulnerable to liquefaction damage in a significant earthquake.

This vulnerability manifested itself in the Canterbury earthquakes from 4 September 2010 onwards, which generated significant liquefaction-related damage to both land and buildings.

The effects of liquefaction may include ground surface subsidence, ejecta, ground cracking, loss of soil strength and lateral spreading, all typically resulting in differential ground surface subsidence. These effects may result in consequential land damage, which subsequently may result in damage to residential buildings on that land.

The severity of the consequential land damage depends on the thickness, strength or stiffness of the non-liquefying soils or crust at the ground surface, which act as a protective raft over the liquefied soils. The greater the depth to liquefying soils, the lesser the effects observed at the surface. The amount of consequential land damage is dependent on the thickness, relative density and the amount of silt- sized particles in the liquefying soil layers. Looser soils and thicker liquefying layers with low percentages of silt-sized particles are likely to have a more adverse effect at the ground surface compared to denser liquefying layers, and liquefying layers that are deeper below the ground surface. Other factors include proximity to rivers or streams. Properties in these areas are more likely to laterally spread compared to properties further away, resulting in consequential damage, even if there is a relatively thick non-liquefying crust.

The liquefaction-related land damage also resulted in subsidence. As a result, the ground surface is closer to the groundwater table, which may increase the vulnerability of land to liquefaction in these areas.[5]

3.2 Ministry of Business, Innovation and Employment (MBIE) guidance

During the CES, the Canterbury Earthquake Recovery Authority (CERA) zoned residential land to prioritise the rebuild. Red zones had area-wide land and infrastructure damage, uneconomic or highly difficult to repair. Green zones were suitable for residential repair/rebuild. To help with foundation rebuilds and repairs the Department of Building and Housing, now the Ministry of Business, Innovation and Employment (MBIE), divided land in the residential green zone into three technical categories. These categories are used with regard to likely future land performance, as a guide to the level of site investigation required and the appropriate foundation systems to be applied. The technical categories:[6]

- Technical Category 1 (TC1) – Liquefaction damage is unlikely in future large earthquakes. Standard residential foundation assessment and construction is appropriate.
- Technical Category 2 (TC2) – Liquefaction damage is possible in future large earthquakes. Standard enhanced foundation repair and rebuild options in accordance with MBIE guidance are suitable to mitigate against this possibility.
- Technical Category 3 (TC3) – Liquefaction damage is possible in future large earthquakes. Individual engineering assessment is required to select the appropriate foundation repair or rebuild option.

To ensure that ground improvement works are appropriately targeted, to achieve the required level of increased resilience, it is necessary to be able to identify land vulnerable to liquefaction. The MBIE (2012) guidelines provide assessment criteria for TC3 properties to identify

[5] Russell, J., van Ballegooy, S., Rogers, N., Lacrosse, V., Jacka, M. *The effect of subsidence on liquefaction vulnerability following the 2010 – 2011 Canterbury Earthquake Sequence.* Proceedings of the 12th Australia New Zealand Conference on Geomechanics, 2015, pp. 610-617.

[6] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Version 3, December 2012.

KEY POINTS

EQC

Geotechnical site specific assessment is required to determine the appropriateness of any ground improvement method endorsed in the MBIE guidelines.

when TC3 foundation solutions or ground improvements should be applied. Following geotechnical investigation and engineering assessment, it may be determined that not all TC3 land requires TC3 foundation solutions or ground improvement.

In 2011[7] and 2012[8] MBIE undertook preliminary ground improvement trials at the disused QEII Park stadium, in Christchurch. The purpose of the trials was to help the development of TC3 foundation solutions for rebuilding with greater resilience on liquefaction-vulnerable land. These solutions are described in the 'MBIE guidance'[9]: *Repairing and rebuilding houses affected by the Canterbury earthquakes.*

The 2011 and 2012 testing indicated that the construction of 2m thick soil-cement rafts, reinforced and re-compacted soil rafts or 8m deep stone column ground improvement solutions decreased the amount of differential ground surface subsidence, as a result of underlying liquefaction, compared to unimproved land.

The MBIE guidance recommended five foundation options for rebuilding residential houses on TC3 land:

1. TC2 foundations (where investigations show this is suitable)
2. 'Hybrid' raft foundation (where calculated settlement is less than 50mm for the 25-year return period levels of earthquake shaking)
3. TC3 surface structure foundations
4. Ground improvement (between 2m and 8m depth) in conjunction with a TC2 foundation
5. Deep piling to a non-liquefiable layer (the conventional approach).

Following the release of the MBIE guidance in April 2012,[10] there was limited use of the ground improvement options for foundations graded as TC2, largely owing to cost considerations and construction constraints on many residential sites.

3.3 New Zealand Earthquake Commission (EQC)

The Earthquake Commission (EQC) administers the statutory scheme of insurance of residential land and buildings against natural disaster damage, this includes liquefaction-related damage to land and buildings caused by earthquakes. As a result of the CES, many properties in Christchurch have subsided and in some suburbs this has increased the vulnerability to liquefaction damage in future earthquakes. Land that has become more vulnerable to liquefaction-induced land damage may be eligible for land damage compensation.[11]

In 2012 desktop pricing of MBIE-endorsed[10] ground improvement methods, which can also be used to repair the increased liquefaction vulnerability, were found to exceed the maximum possible EQC compensation for many of the properties.

[7] Tonkin & Taylor Limited, *Christchurch Ground Improvement Trials Report prepared for Department of Housing and Building,* March 2012.

[8] Tonkin & Taylor Limited, *Christchurch Ground Improvement Trials – Phase 2: Influence of Fill Placement Report prepared for EQC,* 2012.

[9] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Version 3, December 2012.

[10] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes*, Version 2b, April 2012.

[11] Tonkin & Taylor Ltd. *Canterbury Earthquake Sequence: Increased Liquefaction Vulnerability Assessment Methodology,* 2015.

Under section 5 of the Earthquake Commission Act 1993, EQC facilitates research about matters relevant to natural disaster damage, methods of reducing or preventing natural disaster damage and the insurance provided under the Act.

EQC undertook an extensive GIP to develop a range of shallow, lower-cost ground improvement methods that could be used as solutions for properties. The GIP builds on the findings from the QEII Park stadium trials undertaken by MBIE.

As a result the MBIE guidance has recently been updated to incorporate lower-cost foundation solutions, which are expected to mean significant cost savings to the wider earthquake recovery programme.[12]

3.4 Ground Improvement Programme

The GIP was completed in two phases. The GIP began with the Science Trials and ended with the Pilot. The Science Trials began in April 2013 at three locations within Christchurch's red zone.

The Science Trials involved constructing and testing a range of shallow ground improvement methods. The construction and testing works were completed in December 2013.

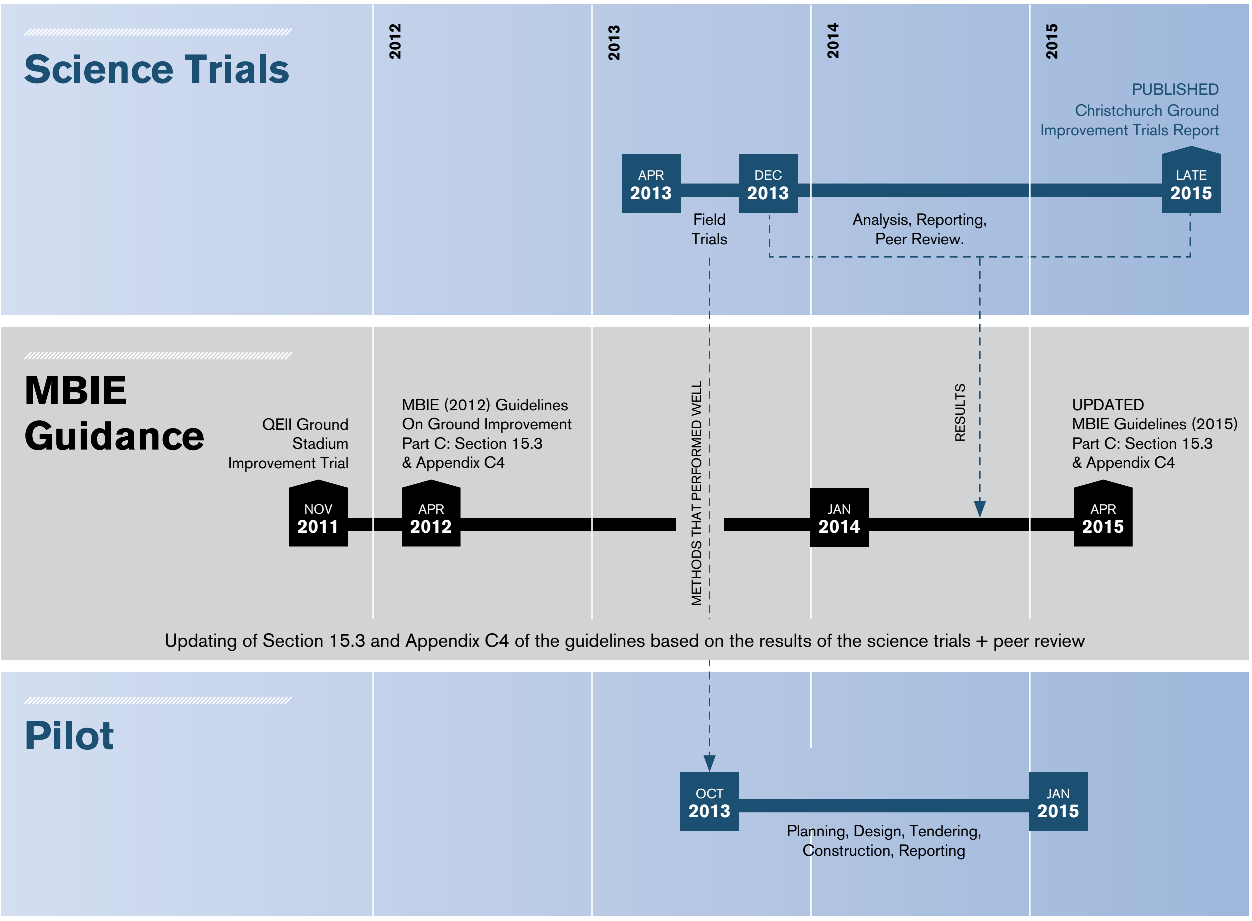
While the results of the Science Trials were being analysed and peer reviewed, ground improvement methods that were assessed as having performed well and were likely to be affordable (based on desktop pricing), were further trialled as part of the Pilot.

Planning for the Pilot began in October 2013, with construction works undertaken throughout 2014. Seven different ground improvement methods were constructed across 31 residential TC3 properties and two residential red zone properties to determine actual construction costs and to ensure each method was practical to construct for typical residential environments.

The timeline of the Science Trials, the Pilot and release of the MBIE guidance is shown in Figure 3.2.

[12] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Section 15.3 update, Version 3a, April 2015.

Figure 3.2: Timeline of MBIE Guidance and the Ground Improvement Programme



4 The Science Trials

4.1 Objectives

The primary objectives of the Science Trials were to:

- Test (prove or disprove) the effectiveness of a number of shallow ground improvement methods that were expected to reduce liquefaction vulnerability of residential properties, i.e. improve the resilience of liquefaction-vulnerable land
- Develop reliable, practical and lower-cost test methods that could be used in the residential TC3 areas to more rapidly verify that the ground improvement methods had been effective in sufficiently strengthening or stiffening the upper soil layers.

4.2 Process

The Science Trials began in April 2013 and involved construction and testing of seven different types of ground improvement, using construction equipment readily available in Christchurch at the time and that could be tested on cleared sites where a house would be demolished and rebuilt.

In addition, because a large number of houses in Christchurch on liquefaction-vulnerable land are repairable, a non-destructive ground improvement method, that could be installed beneath an existing house, was investigated. This was an extremely challenging objective as there were limited options to construct ground improvement beneath an existing building. Cement-based permeation grouting, used in specialist applications worldwide, was initially trialled. However, it was unsuccessful in the fine grained soils susceptible to liquefaction which underlie many parts of Christchurch. As a result, an innovative construction method was developed, Horizontal Soil Mixed (HSM) beams. The HSM beams were subsequently tested during the Science Trials. Each ground improvement method tested in the Science Trials is shown in Figure 4.1.

For a description of the development of HSM beams by Hunter et al. (2015) see Appendix B.

KEY POINTS

Science Trials objectives

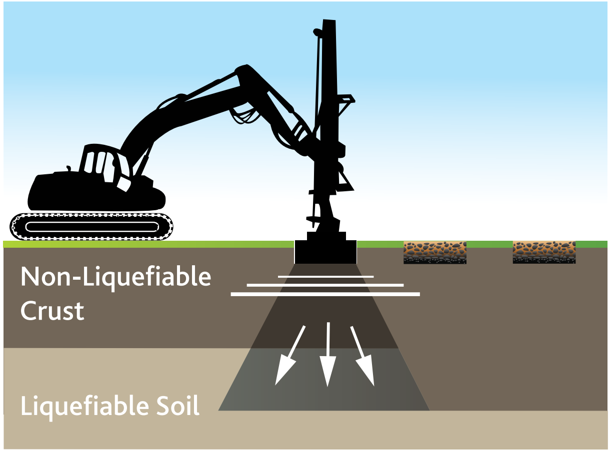
1. **To develop and prove robust and affordable liquefaction mitigation ground improvement solutions that could be constructed on residential properties vulnerable to liquefaction.**
2. **To develop reliable, practical and affordable methods to test and rapidly verify that the ground improvement methods used achieve the required strength and stiffness requirements.**

KEY POINTS

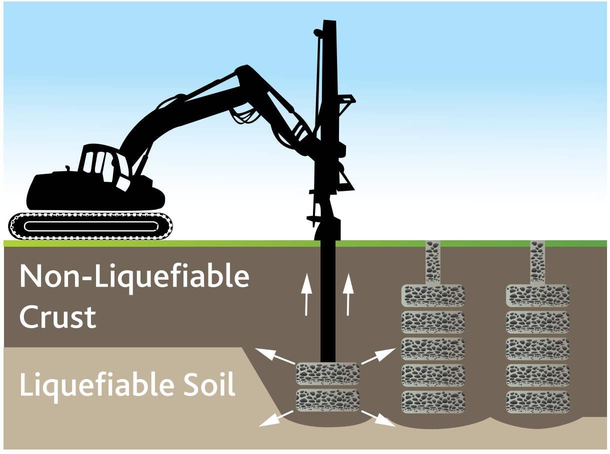
Science Trial process

1. **Seven existing ground improvement methods were trialled for properties where the houses will be rebuilt.**
2. **One new ground improvement method was developed, i.e. Horizontal Soil Mixed beams, for use under existing repairable houses.**

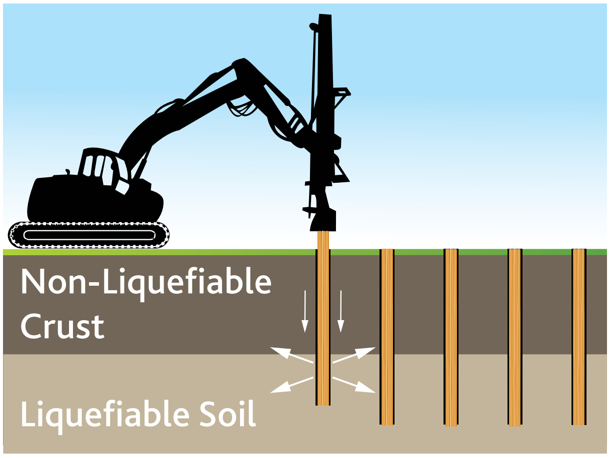
Figure 4.1: Ground improvement methods undertaken during the Science Trials For more information see the Factsheets in Appendix A.



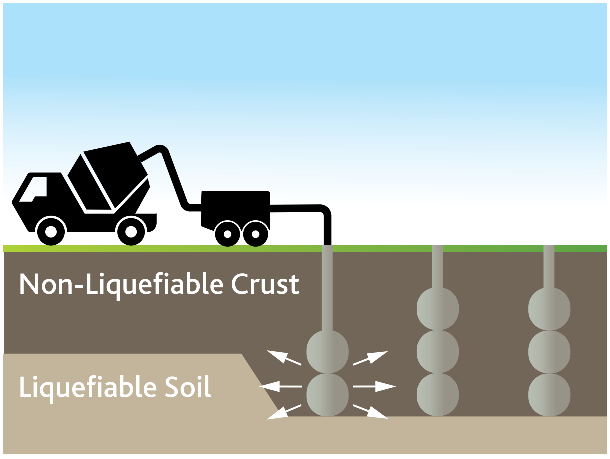
Rapid impact compaction



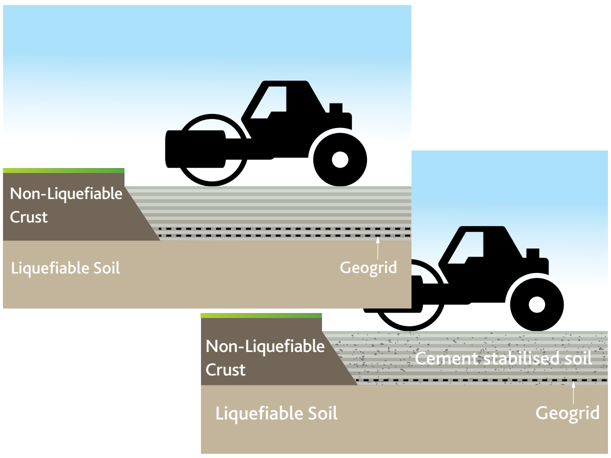
Geopier Rammed Aggregate Pier™ System (RAP)



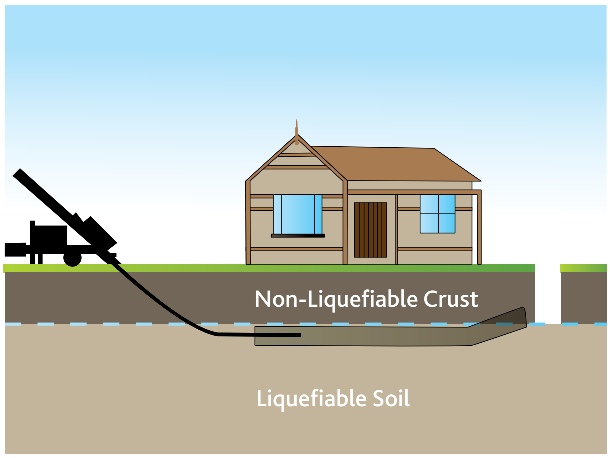
Driven timber poles



Low mobility grout and resin injection



Reinforced gravel raft and reinforced soil-cement rafts



Horizontal Soil Mixed (HSM) beams

4.2.1 Testing ground performance

To evaluate and verify how well each ground improvement method had stiffened or strengthened the ground, a variety of testing techniques were used. These included:

- **Cone penetration tests (CPT)**

This involves hydraulically pushing an instrumented probe into the ground to measure the relative density of the ground before and after completing the ground improvement works. This testing was used to estimate the increase in relative density (strength) of the near-surface soil layers after the ground improvement work.

For more information see Appendix A: What is a cone penetration test?

- **Crosshole geophysical testing**

This testing involves pushing two instrumented probes into the ground several metres apart to measure the velocity with which vibration pulses travel through the soil, before and after completing the ground improvement works. The results of these tests were used to estimate the increase in stiffness of the near-surface soil layers because of the ground improvement work.

For more information see Appendix A: What is crosshole geophysical testing? See Appendix B for a summary of the results of the crosshole geophysical testing of a few of the shallow ground improvement methods by van Ballegooy et al. (2015).

- **T-Rex shake testing (or truck mounted vibrosis testing)**

This involves a large truck placing a vibrating plate onto the ground to simulate earthquake shaking beneath the truck. Sensors in the surrounding ground monitor how the soil is responding and how much shaking is required to trigger liquefaction. This testing was undertaken on both the natural (unimproved) and ground-improved soils to estimate the increase in resistance to liquefaction triggering because of the ground improvement work.

For more information see Appendix A: What is T-Rex shake testing? See Appendix B for a summary of the results of the T-Rex shake testing of a few of the shallow ground improvement methods by van Ballegooy et al. (2015).

- **Blast induced liquefaction testing**

This involves detonating numerous small explosives in the ground in a carefully choreographed sequence to liquefy the surrounding soils underlying the shallow ground improvement works. By doing this, the performance of different types of shallow ground improvement methods were assessed to compare how they reduce differential ground surface subsidence caused by the liquefaction of the underlying soil layers.

For more information see Appendix A: What is blast-induced liquefaction testing? See Appendix B for a summary of the results of the blast-induced liquefaction testing of a few of the shallow ground improvement methods by Wentz et al. (2015).

- **Other testing and investigation techniques**

Other simple on-site testing methods were also done during the Science Trials, including excavation to expose and enable examination of the improved soil layers. This enabled a visual assessment of the improved ground beneath the surface and also to collect soil samples for laboratory testing.

For more information on the Science Trials see Appendix A: What were the Christchurch Ground Improvement Science Trials?

Videos are also on the EQC website at: www.eqc.govt.nz

4.3 Results

4.3.1 Overview

The results from the Science Trials were assessed and analysed between April 2013 and April 2015. During this time the data, assessment and conclusions have been peer reviewed by leading earthquake engineering and liquefaction mitigation experts. Full results and conclusions of the ground improvement Science Trails are currently being published. Summary papers on the test results of the crosshole geophysical, T-Rex shake and blast-induced liquefaction testing of various shallow ground improvements are included in Appendix B on the EQC website www.eqc.govt.nz/GIP. Table 4.1 is a summary of the key results from the Science Trials.

4.3.2 The Science Trial summary

Ground improvement can be undertaken in a range of soil types to mitigate liquefaction vulnerability. In Canterbury, the soils requiring treatment are typically silt to sands. Although there are a range of shallow ground improvement methods proven to provide acceptable levels of ground improvement, some are more effective in sandy soils and less effective in silty soils. Therefore, not every method is technically suitable for every property. Each site will also have practicality issues that need to be considered, such as: groundwater depth, proximity to neighbouring properties, access, where the house will be built relative to the boundaries, and lateral spread risk. The GIP has identified a number of shallow ground improvement solutions of which at least one cleared site solution is likely to be technically applicable to every TC3 property in Canterbury, except those with organic or peat soils.

The soil profiles (geology) from properties that have performed well, i.e. did not experience liquefaction-related damage, through the CES provide the best example of the CPT and crosshole geophysical methods (data outputs) likely to perform well during earthquakes. Generally, properties with thicker, denser or stiffer near-surface soils, i.e. non-liquefying crusts, performed better during the CES compared with properties with thinner, looser and less stiff near-surface soils. These profiles were found to be similar to the post-ground improvement CPT and crosshole geophysical methods, which performed well during the T-Rex shake testing and blast-induced liquefaction testing at the Science Trial sites.

The shallow ground improvement methods all aim to thicken and/or stiffen the near-surface soil layers to reduce liquefaction vulnerability, i.e. replicate the characteristics of natural soil sites that performed well during the CES. The results from the Science Trials showed that shallow ground improvements do not significantly reduce ground surface subsidence as a result of the liquefaction of the underlying soil layers but they improve the crust rigidity and reduce the differential ground surface subsidence that damages buildings on top of the improved ground.

Dense and/or stiff soils are more resistant to liquefaction triggering. The rapid impact compaction and rammed aggregate piers ground improvement methods work well in building thicker non-liquefying crusts, reducing liquefaction vulnerability. Stiff soils (stiff surface crust) behave more rigidly compared to less stiff crusts, reducing the likelihood of differential ground surface subsidence (undulations, tilt and differential settlement). The 1.2m thick shallow reinforced soil-cement and reinforced gravel rafts work well in improving crust rigidity. Driven timber poles do not prevent liquefaction triggering in the near-surface soils but they help to redistribute the weight of the house and make the liquefaction-induced ground surface subsidence more uniform, which means a reduction in differential ground surface subsidence.

HSM beams also work to improve crust rigidity but are built underneath existing buildings. The level of performance achieved with HSM beams is generally lower than cleared site ground improvement methods.

These mechanisms and overall relative performance shown in Table 4.1.

Table 4.1: **Summary of Science Trial Results**

Ground Improvement Method	Soil Type	Mechanism and effectiveness for increasing the thickness of the non-liquefying crust	
		MECHANISM	EFFECTIVENESS
Rapid impact compaction	Sandy	Densification	Good***
	Silty	Densification	Poor
1.2m reinforced gravel raft	Sandy	Replacement with non-liquefying material	Very good**
	Silty	Replacement with non-liquefying material	Very good**
1.2m reinforced soil-cement raft	Sandy	Cementation	Very good**
	Silty	Cementation	Very good**
4m deep Rammed Aggregate Piers†	Sandy	Densification Densifying & Stiffness	Very good
	Silty	Stiffness	Good
4m deep low mobility grout	Sandy	Densification	Poor*
	Silty	Densification	Poor*
4m deep driven timber poles	Sandy	Densification & Stiffness	Moderate
	Silty	Densification & Stiffness	Poor
Horizontal Soil Mixed beams††	Sandy	Stiffness	Moderate
	Silty	Stiffness	Moderate

† For a summary of the results of the performance of Rammed Aggregate Piers by Wissman et al. (2015) see Appendix B.

†† For a summary of the results of the performance of the Horizontal Soil Mixed beams by Wansbone et al. (2015) see Appendix B.

* Poor for shallow/low confined applications.

** Where the groundwater level is greater than 1.2m below the surface these methods do not increase the crust thickness but do increase the crust stiffness.

*** Effectiveness likely to reduce to poor in locations where the depth to groundwater is less than 1.2m below the surface.

Mechanism and effectiveness for reducing the differential ground surface subsidence caused by liquefaction of the underlying soils		Relative overall effectiveness
MECHANISM	EFFECTIVENESS	
Thicker crust	Good***	**Good**
Thicker crust	N/A	**Poor**
Stiffer crust	Good	**Good**
Stiffer crust	Good	**Good**
Stiffer crust	Very good	**Very good**
Stiffer crust	Very good	**Very good**
Stiffer and thicker crust	Very good	**Very good**
Stiffer and thicker crust	Good	**Good**
Thicker crust	Poor*	**Poor***
Thicker crust	Poor*	**Poor***
Stress redistribution	Moderate	**Moderate**
Stress redistribution	Moderate	**Moderate**
Stiffer and thicker crust	Good in one direction marginal in another	**Moderate**
Stiffer and thicker crust	Good in one direction marginal in another	**Moderate**

5 The Pilot

5.1 Objectives

The primary objectives of the Pilot were to:

- Determine the costs, practicalities and risks associated with the various ground improvement methods of the Science Trials
- Determine if some methods were more suitable for residential construction than others
- Assess and establish Canterbury contractor capability to carry out the works
- Enhance the understanding and acceptance of the GIP among interested parties, including homeowners, insurers, engineers, construction companies and regulatory authorities
- Determine consenting requirements.

5.2 Process

Construction of ground improvement works began in late 2013 and were completed at the end of 2014. Ground improvement works were undertaken at 31 residential TC3 properties and two residential red zone properties. The majority of the works were undertaken by locally based contractors. The ground improvement work on each property was competitively tendered, with the exception of the Horizontal Soil Mixed beam works. Construction of HSM beams was only undertaken by one contractor who was appointed to do this as part of the Pilot.

The ground improvement methods included in the Pilot are shown in Figure 5.1.

KEY POINTS

Pilot Objectives

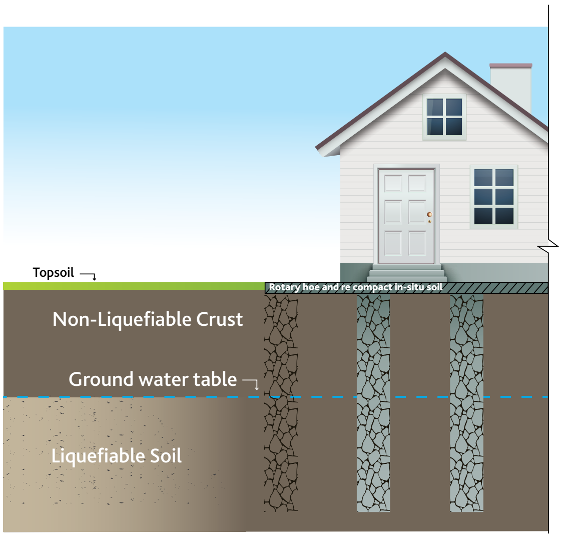
1. **To determine the practicalities and costs associated with construction of the Science Trials ground improvement methods in a residential setting.**
2. **To enhance understanding of ground improvement methods among those interested in repairing or building homes on properties vulnerable to liquefaction.**

KEY POINTS

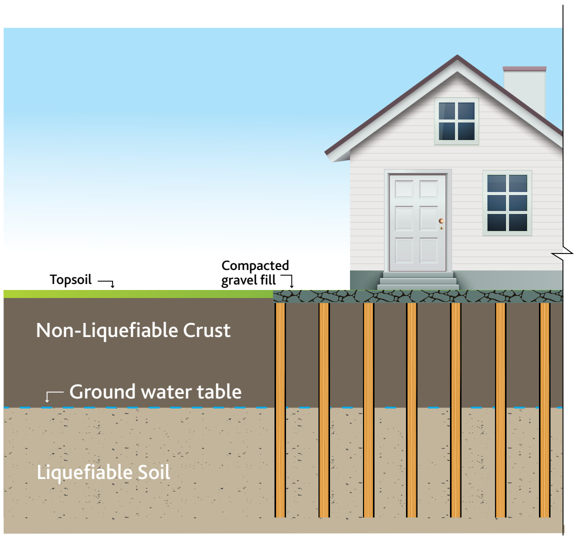
Pilot Process

1. **Five main types of ground improvement were constructed on residential properties in TC3 areas of Christchurch and Kaiapoi to assess real-world application.**

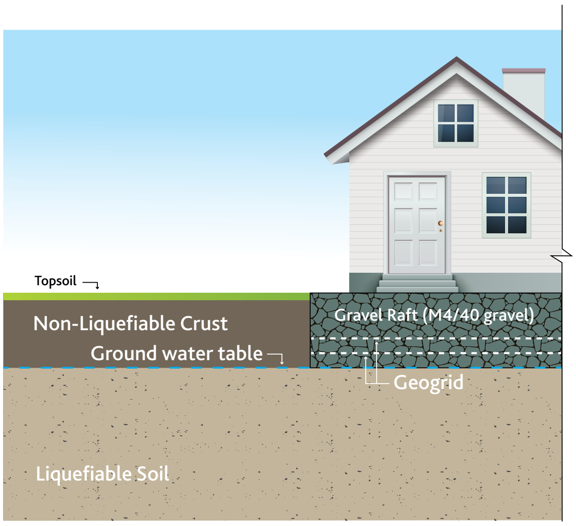
Figure 5.1: Ground improvement methods constructed during the Pilot
See Appendix A for more information.



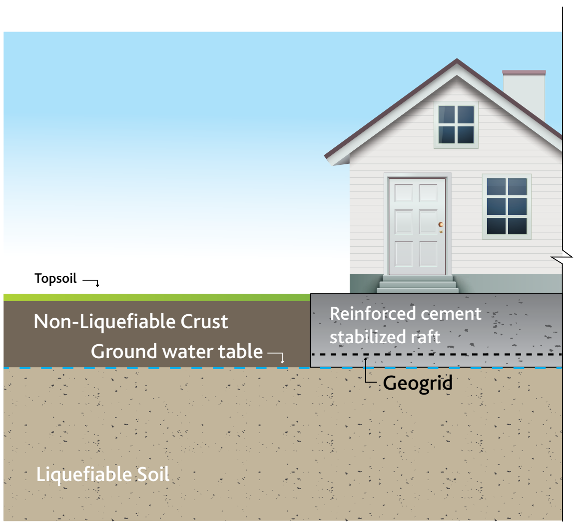
Stone columns



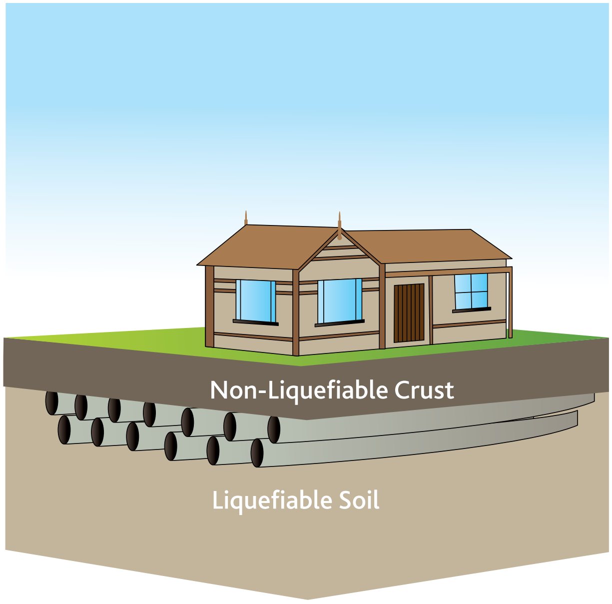
Driven timber poles (2.5 to 4m deep, depending on site ground conditions)



Reinforced gravel rafts (1.2m and 2.0m deep)



Reinforced soil-cement rafts (1.2 to 1.5m deep)



Horizontal Soil Mixed (HSM) Beams

For more detail refer to the Fact Sheets in Appendix A titled "What were the Ground Improvement Pilot Projects?"

Short videos about the Pilot and the different ground improvement methods trialled are also on the EQC website go to: www.eqc.govt.nz

5.3 Results

The results for the specific ground improvement methods piloted during the GIP are shown in Table 5.1.

This table summarises and compares the site characteristics, construction considerations, regulatory requirements and effectiveness of liquefaction mitigation of the different methods. The methods according to the MBIE guidance[13] are:

- Type G1 – Shallow densified crust
- Type G2 – Shallow cement stabilised crust
- Type G5 – Crust reinforced with inclusions – composite strengthened crust.

Note type G3 and type G4 are deeper ground improvement solutions which were included in the April 2015 MBIE update[14] and predate the GIP.

For more information refer to Section 3.2 MBIE guidance.

Some methods are more suitable than others depending on the characteristics of the site. Some limitations may be able to be overcome with specific engineering design.

This summary table complements the work of the MBIE guidance. For the design constraints and approaches please see the MBIE guidance.

[13] MBIE guidance, *Repairing and rebuilding houses affected by the Canterbury earthquakes*, Section 15.3 update, Version 3a, April 2015.

[14] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes*, Version 2b, April 2012.

Table 5.1: **Summary of results for the Pilot ground improvement construction methods**

5.3.1 Contractor Capability

The Pilot highlighted that ground improvements were not commonly constructed on residential sites, so local contractors had limited knowledge or the specialist equipment required to do the work.

The Pilot tender helped to stimulate the residential ground improvement market, promoting the new science and economic opportunity among contractors.

The Science Trials and subsequent changes to MBIE guidance and the Pilot have provided more affordable ground improvement options for those building on land vulnerable to liquefaction in Canterbury. The reduction in depth of treatment for reinforced soil-cement rafts and reinforced gravel rafts means dewatering and excavation support in most cases and specialised plant is not needed.

Of the cleared site shallow ground improvement options piloted, only Rammed Aggregate Piers and stone columns require further investment and competition in the market to stabilise costs and supply. The other methods do not require specialist plant or skilled labour, so smaller contractors could be encouraged to do this work.

The HSM beams method is currently the only ground improvement method for under existing repairable homes. As the HSM beams method was developed during the Science Trials only one contractor has the specialist modified equipment needed for residential construction.

Table 5.1: **Summary of results for the Pilot ground improvement construction methods**

	Generic name	MBIE guidance ground improvement type	Description	Nominal thickness of treatment below base of foundation	Site characteristics: Suitable for residential areas	Site characteristics: Effective at greenfield subdivision sites (i.e. prior to public sale and release)	Site characteristics: Good method to manage contaminated sites	Construction considerations: Standard construction equipment	Construction considerations: Small site access	Construction considerations: Approximate construction duration per property (excluding pre-construction preparation and any necessary curing time)	Construction considerations: Low risk of weather delays	Construction considerations: Low construction monitoring requirements	Construction considerations: Low requirement for verification testing	Construction considerations: No dewatering or excavation support required	Construction considerations: Minimal disposal of materials offsite	Construction considerations: Minimal imported materials	Construction considerations: Minimal on-site stockpile or working area requirements	Construction considerations: Low dust nuisance potential	Construction considerations: Low noise and vibration potential	Construction considerations: Suitable to construct close to boundary	Construction considerations: Low volumes of construction traffic movement to and from site	Liquefaction mitigation: Effective in sandy soil layers	Liquefaction mitigation: Effective in silty soil layers	Liquefaction mitigation: Effective in organic and peat layers	Liquefaction mitigation: Effective in moderate lateral spread	Additional information
CLEARED OR GREENFIELD SITE	**Shallow densified crust (MBIE type G1)**	**G1c**	**Rapid impact compaction**	4.0m	✘	✔	✔	✘	✘	2 to 3 days	Y/N	Y/N	✘	✔	✔	Y/N	✔	Y/N	✘	✘	✔	✔	✘	✘	✘	Fill material required to infill depressions in the ground caused by compaction. Up to 0.5m of fill needed to reinstate.
		G1d	**Reinforced gravel raft**	1.2m	✔	Y/N	✘	✔	Y/N	2 to 3 weeks	✘	Y/N	✘	Y/N	✘	✘	Y/N	✔	Y/N	✔	✘	✔	✔	✔	✔	Gravel needs to be crushed in accordance with the MBIE guidance. Pre ordering of gravel maybe required. Correct grid placement at bottom of excavation can be difficult.
	Shallow cement stabilised crust (MBIE type G2)	**G2a**	**Ex-situ soil-cement mixing**	1.2m	✔	Y/N	✘	✘	Y/N	1 to 2 weeks	✘	✘	✘	Y/N	Y/N	Y/N	✘	✘	Y/N	✔	Y/N	✔	✔	Y/N	✔	Soil can be imported to bring the stabilised crust up to finished level if increased densification achieved during recompaction is high. Increased traffic movement.
		G2a	**Rotovated* soil mixed**	1.2m	✔	Y/N	✘	✔	✔	1 week	✘	✘	✘	Y/N	Y/N	Y/N	Y/N	✘	✔	✔	✔	Y/N	✔	Y/N	✔	An aggregate working platform may be required at base of excavation.
		G2b	**In-situ soil mixing**	2.0m	✔	Y/N	Y/N	✘	✘	1 to 2 weeks	Y/N	✘	✘	✔	Y/N	Y/N	Y/N	Y/N	Y/N	Y/N	✔	✔	✔	✘	✘	Minimum strength requirements and mixing consistency can be difficult to achieve.
	Composite strengthened crust (MBIE type G5)	**G5a**	**Shallow stone columns**	4.0m	Y/N	✔	✔	✘	✘	1 week	Y/N	Y/N	✘** ✔***	✔	✔	✘	Y/N	✔	Y/N	Y/N	Y/N	✔	✘	✘	✘	Ground movement should be monitored at adjoining properties.
		-	**Rammed aggregate piers**	4.0m	✔	✔	✔	✘	✘	1 week	Y/N	Y/N	✘** ✔***	✔	✔	✘	Y/N	✔	Y/N	Y/N	Y/N	✔	Y/N	✘	✘	Ground movement should be monitored at adjoining properties.
		G5b	**Driven timber poles**	4.0	Y/N	Y/N	✔	✔	✔	1 to 2 weeks	✔	✔	✔	✔	✔	✘	Y/N	✔	Y/N	Y/N	✔	Y/N	Y/N	Y/N	✘	No significant implications for properties with contaminated land.
UNDER EXISTING BUILDINGS		**-**	**Horizontal Soil Mixed beams******	2 x 0.5m	✔	✘	Y/N	✘	Y/N	2 weeks	Y/N	Y/N	✘	✔	✔	Y/N	Y/N	✔	Y/N	✘	✔	✔	✔	✘	Y/N	Relatively expensive. Reinstatement works may be required to repair damaged surfaces. Minor ground movement may result in minor changes to internal floors.

Note:

✔ = Yes ✘ = No Y/N = Maybe (potential limitations)

* A variation on ex-situ soil cement mixing.

** Specific design so requires verification testing. A paper highlighting the importance of verification testing by Wotherspoon et al. (2015) is provided in Appendix B.

*** Standard design that is conservative and does not require verification testing.

**** Horizontal soil mixed beams does not achieve the same level of performance as the cleared site ground improvement solutions and is therefore only suitable underneath existing buildings.

KEY POINTS

Contractor Capability

1. **The GIP and subsequent changes to regulatory guidance have provided more affordable ground improvement options to those interested in rebuilding on existing residential land vulnerable to liquefaction in Canterbury and opened up the residential ground improvement market to smaller non-specialised contractors.**
2. **Several cleared site ground improvement methods have been identified that do not require specialist plant or skilled labour so existing contractors can now do this work if demand increases.**
3. **HSM beams require specialist plant and labour. Currently only one contractor has the specialist equipment to do this work and has only undertaken the work in the Pilot.**

5.3.2 Consenting

The resource consent process was identified in the early stages of the Pilot project as one of the potential obstacles to completing ground improvement works in a timely and efficient manner.

EQC and T+T facilitated presentations, workshops, and site visits to help local government consenting officials develop a better understanding of liquefaction vulnerability and shallow ground improvement methods. The GIP aimed to identify opportunities to simplify consenting processes and to develop relationships with consenting authorities, to build understanding and confidence around the purpose and nature of the ground improvement solutions proposed.

Subsequent changes to regional and city plans, led by CERA, have streamlined the consenting process and significantly reduced the number of consents required for ground improvement works, reducing costs and administration to landowners, agents and regulatory authorities.

For more information see the Factsheets in Appendix A:

What is a Resource Consent and why do I need one for ground improvement?

and

What is a Building Consent and why do I need one for ground improvement?

5.3.3 Ground improvement costs

One of the objectives of the Pilot was to assess the costs of the various ground improvement methods to ensure that affordable methods are developed for long-term application throughout New Zealand. While in some cases the Pilot undertook ground improvement methods with specifications that were closely aligned with MBIE guidance at the time of installation, the itemised rates that were received in tenders have enabled the Pilot's quantity surveyors, Kingston Partners Limited, to estimate rates based on the updated MBIE guidance.[15]

The cost structure and rates for the ground improvement works were sourced from 12 construction contracts incorporating 31 properties in the TC3 area and two in the residential red zone. The contracts were a combination of open and invited tenders to establish market related prices under normal construction conditions. Contracts were carried out under the general provisions of NZS 3910:2003 Conditions of contract for building and civil engineering construction.

A summary of approximate ground improvement costs from the Pilot properties are shown in Table 5.2. For more information see the Kingston Partners Limited report.[16]

Table 5.2: **Summary of indicative construction costs as determined in the Pilot for selected ground improvement types, in accordance with MBIE (2015) guidance**

MBIE (2015) specified ground improvement method	Approximate cost per m^2 of treated footprint (excl GST)	Minimum ground improvement area treated for footprint of $146m^2$ (m^2)	Approximate cost for house footprint of $146m^2$ (excl GST)
1.2m thick reinforced gravel raft	$176 to $225	204	$36,000 to $46,000
1.2m thick reinforced soil-cement raft	$180 to $230	204	$37,000 to $47,000
4m deep stone columns	$145 to $195	270	$39,000 to $53,000
4m deep driven timber poles	$240 to $270	270	$65,000 to $73,000
Horizontal Soil Mixed beams	$410 to $522	268	$110,000 to $140,000

Note:

* Rates sourced from Kingston Partners Limited report[16] and the HSM pilot project closure report[17].
* Construction related costs only from the Pilot. Additional costs are required for enabling works, engineering, design, project management, consenting and regulatory compliance and repair works.
* All rates exclude GST, are indicative and do not include an allowance for contingencies and risks due to unexpected ground conditions. These may be higher in the case of HSM beams due to the possibility of damage to the existing house during the construction process.
* Treatment areas vary between methods owing to variations in the required treatment area beyond the house footprint.
* $146m^2$ from MBIE guidance as a representative the average house footprint size in Christchurch.
* HSM beam rates are from a single contractor in a 'proof of concept' pilot.

[15] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Section 15.3 update, Version 3a, April 2015.

[16] Kingston Partners Limited, *Report on Ground Improvement Costs for Cleared Sites in the Canterbury Area* (in press).

[17] Stretton Consulting Limited, *Ground Improvement Pilot Project, Horizontal Soil Mixed beams Proof of Concept Summary Report* (in press)

KEY POINTS

Cost of MBIE guidance ground improvement methods

1. Four methods of ground improvement included in the MBIE guidance for cleared sites can be constructed for approximately $36,000 - $73,000 (excl GST) for houses with a footprint of 146m² (non-construction related costs, such as design and consenting, are not included in this estimate).

2. A new method of ground improvement (HSM beams) that can be constructed beneath some existing and repairable houses costs approximately $110,000 - $140,000 (excl GST) for houses with a footprint of 146m2 (note non-construction related costs are not included in this estimate).

5.3.4 Holistic Approach

The Pilot was run collaboratively with insurers and their project management teams. It engaged widely with parties interested in building on residential liquefaction-vulnerable land to promote the GIP learnings and to understand the end-to-end rebuild process from a customer perspective.

Working on representative homes in Canterbury with typical constraints highlighted that ground improvement and house foundations are best designed collaboratively to save costs.

Ground improvement is complex, similar to managing a house rebuild. There are efficiencies to combining ground improvement and surface rebuilds in terms of design and project management fees, enabling works and consenting costs, lower foundation costs and greater flexibility in cladding and roofing systems.

The use of ground improvement methods on sites within the Christchurch City Council Flood Management Areas may be constrained by specific floor level and foundation requirements. Flood Management Areas were identified to reduce future damage to the city from major floods and rising sea levels.

Early engagement between the structural and geotechnical engineer will generally enable a more efficient and holistic assessment of ground improvement and foundation options.

5.3.5 The Pilot results summary

The Pilot successfully implemented ground improvement methods that are consentable and can be practically constructed to provide an appropriate level of protection for houses on land vulnerable to liquefaction-induced damage.

The Pilot identified the practical constraints that need to be considered when assessing the method for a site, such as groundwater depth, soil conditions, proximity to neighbouring properties, access, where the house will be built relative to the boundaries, lateral spread risk, soil contamination and building during wet or windy weather.

The GIP has shown that almost all TC3 property in Canterbury has an applicable cleared site ground improvement solution, except for organic or peat soil sites. Organic or peat soils are approximately less than 5% of TC3 properties.

For some properties with repaired or existing houses, the new experimental HSM beam ground improvement method is potentially available but owing to access constraints, properties being too close to boundaries, and ground water levels, there are many where this method cannot be applied.

When assessing which ground improvement solution is best for a site, all risks and potential constraints should be considered. For instance, while reinforced gravel rafts are likely to be the most economical and universally applicable method, costs may inflate in winter months because of weather delays, contaminated sites will have expensive soil disposal costs and a high water table will require additional design elements. Any of these constraints could make other methods, such as stone columns more appropriate and affordable.

5.4 Lessons and Outcomes

5.4.1 General/Technical

a. When sites are clearly predicted as being vulnerable to liquefaction, ground improvement may be considered as an option to mitigate liquefaction damage.

b. The GIP validated earlier international work that proposed the presence of a thick/stiff non-liquefying crust is effective at mitigating liquefaction damage in residential areas.[18] This was demonstrated by the CES and also by the blast-induced liquefaction testing performed in the Science Trials.

c. Shallow ground improvement can be effective at creating a non-liquefying crust and reducing a site's vulnerability to liquefaction damage.

d. While some ground improvement methods may be technically better than others, there are a number of methods that can be effective for most cleared sites, and the best solution must be selected on a case-by-case basis once all site issues have been assessed.

e. Ground improvement should be verified on site, because even good methods may not work well in unfavourable soil conditions or if the construction quality is poor and has defects.

f. Ground improvement and house foundation options are best considered and designed together, especially in the Flood Management Areas, where minimum floor level elevations can impact the type of suitable foundations.

g. Early engagement between the structural and geotechnical engineers will enable a more efficient and holistic assessment of ground improvement and foundation options.

h. Ground improvement in organic/peat soils can be problematic and is not generally recommended. Where organic/peat soils are present within 1.2m of the ground

[18] Ishihara, K. 1985. *Stability of natural deposits during earthquakes.* Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, CA: 321-376.

surface, a 1.2m thick reinforced gravel raft is likely to be the most appropriate solution. as the peat soils would need to be excavated and removed. Where peat soils are at greater depths, specific engineered design may allow ground improvement to proceed. However, there will be some sites where ground improvement is not suitable at all.

i. Appropriate checks should be made to see if the property is listed on the Hazardous Activities and Industries List (HAIL).[19] If it is listed, or if contaminated soils are found during ground improvement works, an Environmental Scientist should be contacted for professional advice.

j. Contaminated materials, such as cement fibre board containing asbestos, are sometimes left on site following demolition. It is recommended that appropriate checks are made to ensure there are no visible asbestos fragments prior to starting ground improvements to avoid health and safety issues during construction.

k. Appropriate checks should be made to check if the property is listed on the New Zealand 'archaeological site recording scheme'. If the property is listed, or if archaeological artefacts are found during ground improvement works, an Archaeologist should be contacted for professional advice.

5.4.2 Construction

a. As a result of the GIP, construction costs of ground improvement for cleared residential land is now more affordable owing to:

 – the reduced depth of treatment required
 – refinements in construction techniques that require non-specialist skills and/or equipment.

b. Contractors in Canterbury have upskilled to enable them to carry out a wider range of cleared site ground improvement methods. This knowledge and skill base is expected to extend to other parts of New Zealand.

c. One contractor has developed the specialist modified equipment necessary to construct HSM beam ground improvements.

d. Additional attention to Quality Assurance is required as a result of a reduced depth of treatment (as described in the MBIE guidance) to ensure that contractors apply shallow ground improvement in residential areas appropriately.

e. Ground improvement can damage tree roots and lead to stress or the death of a tree. Property owners wanting to keep trees may need to reposition their houses (and the ground improvement footprint).

5.4.3 Regulatory

a. There are now 'shallow' (less than 4m deep) ground improvement methods available for improving the performance of residential land during earthquake events that trigger liquefaction. They are included in the MBIE guidance.

b. MBIE guidance specifies that ground improvement should extend beyond the footprint of houses by between 1m – 2m, depending on the method used. This may affect where the house is positioned. Specific engineering design of the foundation systems can reduce this requirement, where houses need to be built closer to the boundaries.

c. Obtaining a Building Consent for ground improvement work has been streamlined by Christchurch City Council for the methods endorsed by the MBIE guidance.

 – Christchurch City Council requires a Building Consent Exemption, or a Building Consent, to be approved prior to undertaking ground improvement works. A Building Consent for both ground improvement and the house can be granted if the design of the ground improvement and the house are lodged at the same time. This option is preferable.

[19] Ministry for the Environment (MfE) *Hazardous Activities and Industry List (HAIL) identifying most situations in New Zealand where hazardous substances could have caused land contamination.*

d. All local councils (Christchurch City, Waimakariri and Selwyn) require a Resource Consent if the designed ground improvement does not comply with the respective local City or District Plan rules.

e. Waimakariri District Council and Selwyn District Council have advised they do not require Building Consents before undertaking shallow ground improvement works. For residential properties, they consider any ground improvement undertaken on a site while assessing a Building Consent application.

f. The Christchurch City Council lists some trees as being 'heritage and notable trees'. These trees cannot be damaged or removed from the property and ground improvement should be designed to avoid stress or damage to these trees.

g. Considerations should be given to the Flood Management Areas when determining what foundation and ground improvement combinations will be suitable for the proposed house.

h. A standard specification is being developed by the New Zealand Geotechnical Society and MBIE for selected ground improvement methods. This specification will promote a common approach for engineers and contractors for design and construction. The aim of the specification is to streamline the standardisation of construction details and materials, lowering costs for undertaking shallow ground improvement. The basis of these specifications was developed as part of the Pilot.

For more information see Appendix A: What are standard specifications?

5.4.4 Community

a. A holistic approach that considers the land and the house together when rebuilding on liquefaction-vulnerable land will provide more options and better outcomes for property owners.

b. Clear communication of the expected performance of foundation options helps decision-making.

c. Undertaking ground improvement as part of a design and build project requires clear communication and coordination among parties, including neighbouring land owners, consenting officials, contractors and designers.

d. Pre-construction building condition surveys on close neighbouring properties are encouraged for ground construction works to verify or mitigate concerns about potential vibration damage. Pre-construction surveys were undertaken in the Pilot.

KEY POINTS

Ground Improvement Programme Results

1 The results are useful to those interested in repairing or building houses on properties vulnerable to liquefaction, including: property owners, engineers, builders and property developers, private insurance companies, local authorities and central government agencies.

2 The Science Trials tested how well ground improvement methods performed when the underlying soil layers are liquefied. The data showed that differential ground surface settlement, which causes damage to houses when the underlying soil liquefies during earthquakes, can be satisfactorily controlled with the construction of shallow, ground improvement works in conjunction with a TC2 surface structure foundation system.

3 The GIP successfully tested and piloted ground improvement methods that are consentable and can be practically constructed for an appropriate level of protection for houses on land vulnerable to liquefaction-induced damage.

4 The GIP has demonstrated the value of achieving a balance between improving the land and improving foundation strength for better outcomes for property owners.

6 Integrated Foundation Solutions

6.1 Approximate construction costs

The MBIE guidance[20] considers that for TC3 properties, shallow ground improvement should be carried out in conjunction with specified TC2 stiff foundation elements or re-levellable timber floor solutions, forming an integrated foundation solution.

Alternatively, a TC3 foundation solution can also be used.

To determine if an integrated foundation solution is cost comparable to a TC3 surface structure foundation, Kingston Partners Limited carried out a desktop study in May 2015, using cost data[21] from the GIP, to estimate current market construction costs. Other relevant assumptions are outlined below. A summary for ground improvements for TC2 foundations are shown in Table 6.1. To compare costs of foundation systems in conjunction with ground improvements costs for selected TC3 surface structure foundations are shown in Table 6.2.

Table 6.1: **Construction cost ranges (excl GST) for selected integrated foundation solutions with shallow ground improvement and TC2 foundations**

	TC2 Type 1 – Foundation slab overlying gravel raft	**TC2 Type 2 –** 300mm thick concrete slab	**TC2 Type 3 –** Foundation beam grid and slab	**TC2 Type 4 –** Waffle slab foundation	**TC3 Type 1 –** Modified light weight platform with timber piles and plywood perimeter bracing
1.2m Reinforced Gravel Raft (G1d)	Not compatible	$63,000 – $79,000	Not compatible	$62,000 – $78,000	$68,000 – $85,000
1.2m Reinforced soil-cement raft (G2a)	Not compatible	$64,000 – $80,000	Not compatible	$63,000 – $79,000	$69,000 – $86,000
4m Stone Columns (12% to 18% ARR) (G5a)	Not compatible	$66,000 – $86,000	Not compatible	$65,000 – $84,000	Not compatible
4m Driven Timber Poles (1.1m c/c with 250mm SED poles; 5% ARR) (G5b)	Not compatible	$90,000 – $102,000	Not compatible	$89,000 – $101,000	Not compatible

Note:

* Costs are estimates only.
* Costs are based on a building floor area of 146m^2.
* Costs exclude GST, site investigation costs, engineering and project management fees and consenting fees.
* Ground improvement cost data sourced from Kingston Partners Limited cleared sites pilot costing report.[21]
* Foundation costs are estimates only and were sourced from a desktop study by Kingston Partners Limited for providing an indicative cost comparison between TC3 surface structure foundation and ground improvement solutions.
* Foundation and ground improvement options according to MBIE guidance (updated April 2015).
* ARR = Area replacement ratio

[20] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Section 15.3 update, Version 3a, April 2015.

[21] Kingston Partners Limited, *Report on Ground Improvement Costs for Cleared Sites in the Canterbury Area*, (in press)

Table 6.2: **Construction cost ranges (excl GST) for selected TC3 foundations**

	TC3 Hybrid – 600mm thick gravel raft with geogrid and TC2 Type 300mm thick concrete slab	**TC3 Type 1 –** Modified light weight platform with timber piles and plywood perimeter bracing	**TC3 Type 2a –** Timber piles with 150mm thick concrete slab on 600mm thick gravel raft with geogrid	**TC3 Type 2b –** Timber piles with 300mm thick concrete slab on 600mm thick gravel raft with geogrid	**TC3 Type 3 –** Re-levellable platform on waffle slab foundation
Approximate range of costs	$49,000 – $59,000	$33,000 – $40,000	$59,000 – $71,000	$67,000 – $80,000	$56,000 – $68,000

Notes:

* Costs are estimates only.
* Costs are based on a building floor area of 146m².
* Costs exclude GST, site investigation costs, engineering and project management fees and consenting fees.
* Foundation costs are estimates only and were sourced from a desktop study by Kingston Partners Limited for providing an indicative cost comparison between TC3 surface structure foundation and ground improvement solutions.
* Foundation options according to MBIE guidance (updated April 2015).

These rates are an approximate guide, and may vary across different sites, between contractors and as the market for ground improvement matures.

Comparing Table 6.1 of integrated foundation solutions (comprising shallow ground improvement and appropriate TC2 foundations) and Table 6.2 of TC3 surface structure foundations shows that in some cases integrated foundation solutions are cost comparable to TC3 surface structure foundations.

While integrated foundation solutions and TC3 surface structure foundations both meet the requirements of the New Zealand Building Code, they perform differently. Integrated foundation solutions are expected to perform better in earthquakes that trigger liquefaction and are expected to be less likely to need re-levelling, compared to the shallow TC3 surface structure foundation solutions.

6.2 Applications of Ground Improvement Methods

The MBIE guidance[22] specifies a number of criteria and models based on specific geotechnical assessment to determine which foundation systems and ground improvement methods are appropriate for use on various soils in the rebuild of Canterbury. It is likely that there is at least one cleared site shallow ground improvement solution that can be applied at every TC3 property in Canterbury, except those with organic or peat soil layers – approximately 5% of TC3 properties.

In lateral spread areas shallow TC3 surface structure foundation solutions and 1.2m thick soil-cement and reinforced gravel rafts with TC2 type foundation systems are generally the only solutions that can be applied. The other ground improvement methods are generally not suitable for lateral spread areas in the absence of a specifically designed solution.

Figure 6.1 Provides maps showing the applicability of cleared site shallow ground improvement and foundation solutions for TC3 properties at a regional scale based on the geotechnical data available in the Canterbury Geotechnical Database and the criteria in the MBIE guidance[22] for Christchurch.

It is noted that site specific investigation may provide results that vary from the map.

a) Indicative location where TC1, TC2 and TC3 type foundation systems can be used on cleared sites in the TC1, TC2 and TC3 areas.

b) Indicative location where 1.2m thick soil-cement and reinforced gravel rafts in conjunction with TC2 type foundation systems can be used on cleared sites in the TC3 areas.

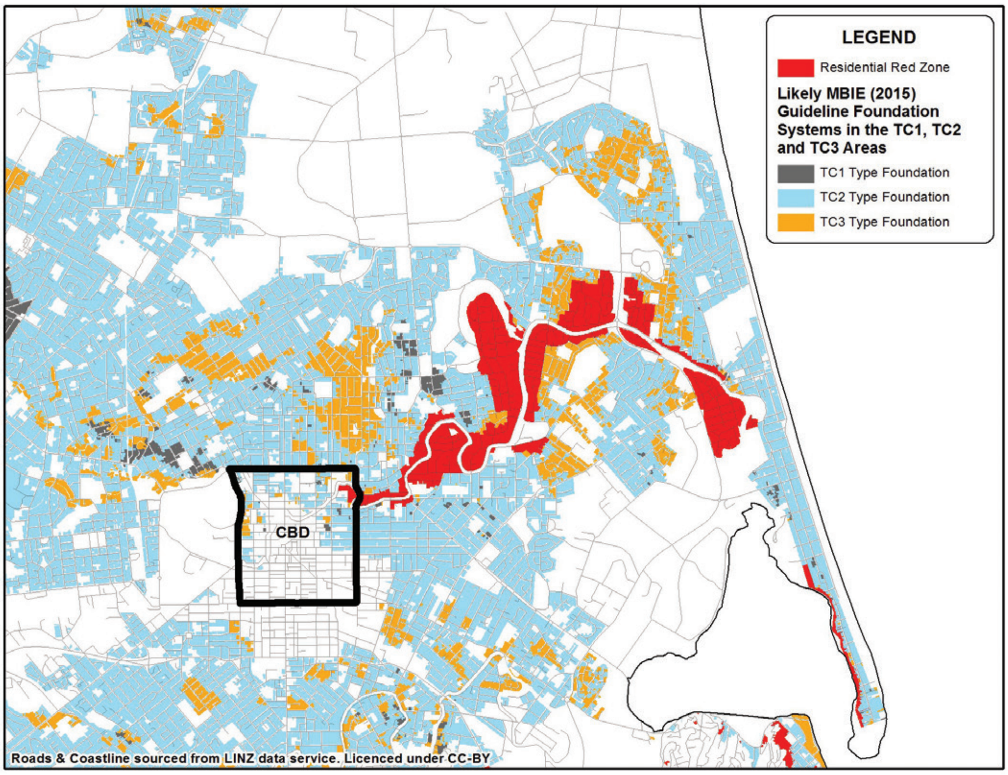
c) Indicative location where 4m deep rammed aggregate piers or stone columns in conjunction with TC2 type foundation systems can be used on cleared sites in the TC3 areas. It is noted that rammed aggregate piers and stone column ground improvements require construction verification testing to demonstrate that the post-improvement soils achieve the target densities specified in the MBIE guidance.[22] Rammed Aggregate Piers and stone column ground improvements are less effective in silty soils compared to sandy soils. A scale of the likelihood that the Rammed Aggregate Piers and stone column ground improvement will achieve the target criteria is shown in Figure 6.1c. The dark green areas indicate a very high likelihood (close to 100%) and the light green shading indicates a very low likelihood (close to 0%) that Rammed Aggregate Piers and stone column ground improvement will be successful.

d) Indicative location where 4m deep driven timber poles in conjunction with TC2 type foundation systems can be used on cleared sites in the TC3 areas.

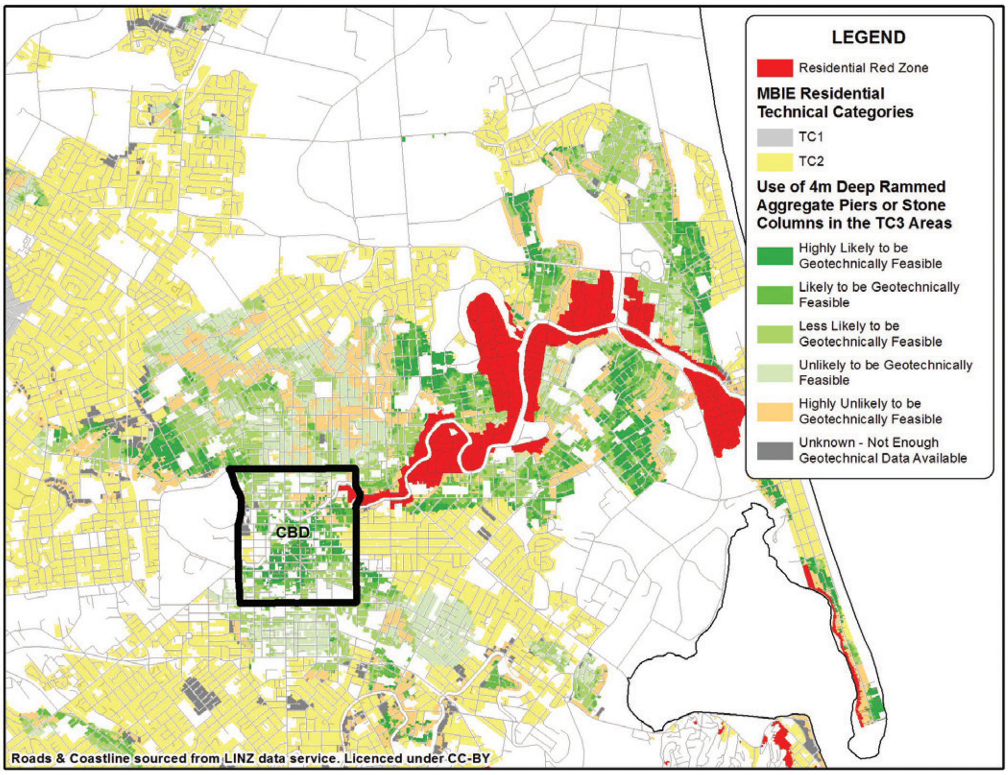
[22] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Section 15.3 update, Version 3a, April 2015.

Figure 6.1: Integrated foundation solutions for TC1, TC2 and TC3 properties in Christchurch based on the criteria in the MBIE guidance[23]

a. Likely foundation system applicable in Christchurch

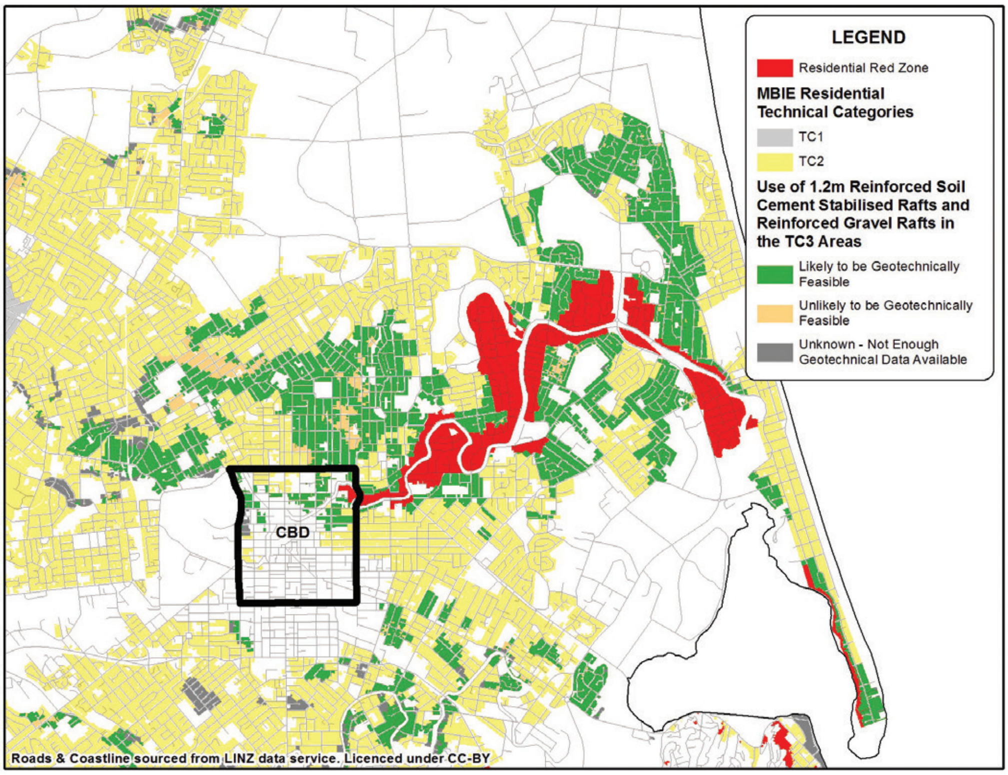


c. Applicability of stone columns and Rammed Aggregate Piers in TC3 areas

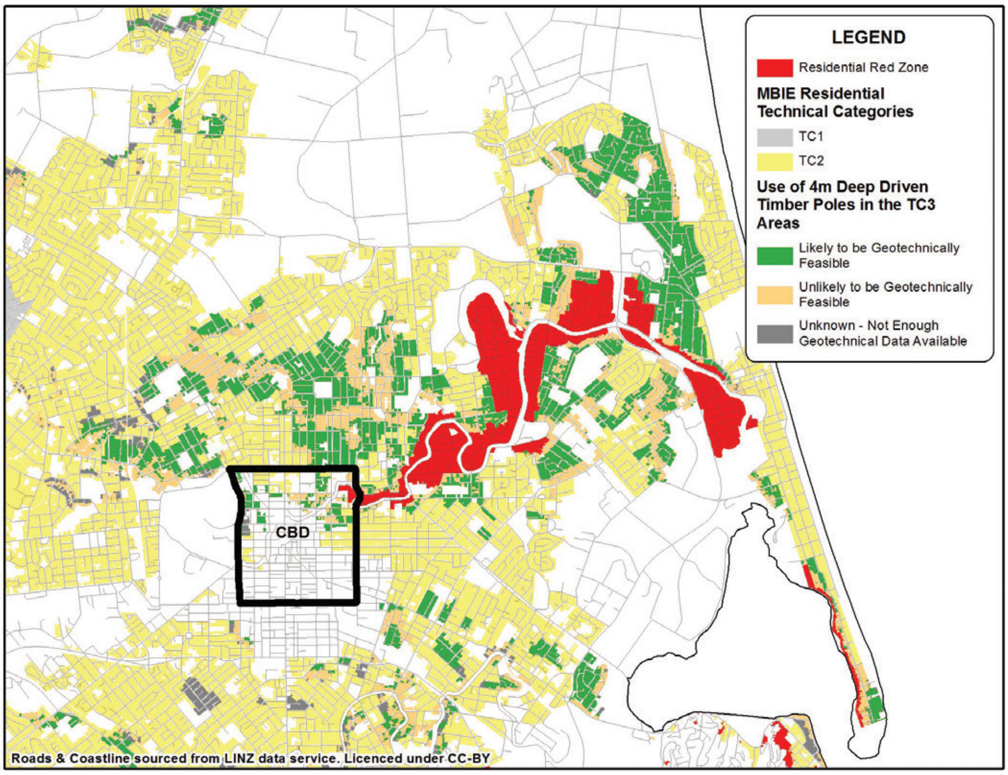


[23] MBIE guidance document, *Repairing and rebuilding houses affected by the Canterbury earthquakes,* Section 15.3 update, Version 3a, April 2015.

b. **Applicability of soil-cement rafts and reinforced gravel rafts in TC3 areas**



d. **Applicability of driven timber poles in TC3 areas**



7 New Zealand and global relevance

The GIP has facilitated a significant step forward in the research of methods to affordably mitigate liquefaction vulnerability of residential houses. While the GIP was primarily driven by the needs of the Canterbury community following the CES, the learned science and other technical and practical lessons can be applied throughout New Zealand and globally. For example, there are other liquefaction-vulnerable residential areas in New Zealand that could benefit from adopting some of the recently proven shallow ground improvement methods for infill housing and replacing old buildings. The benefits would be the same as those seen in Canterbury, i.e. that shallow ground improvement to cleared sites will offer increased resilience at a more affordable price.

For new residential developments, e.g. subdivisions, the approach of improving the ground directly surrounding a house only is less desirable. New residential land should either avoid areas vulnerable to liquefaction or involve ground improvement that is better suited to an area-wide scale.

KEY POINTS

Relevance

1 **The lessons from the GIP are relevant and valid throughout New Zealand for residential properties assessed as vulnerable to liquefaction.**

2 **The GIP and the results from the Science Trials have been a successful research project and the resulting data is recognised for its global significance.**

3 ***Residential Ground Improvement findings from trials to manage liquefaction vulnerability* report assists in the application and education of practical lessons to stakeholders.**

4 **Where new subdivisions are planned in areas susceptible to liquefaction the GIP offers practical solutions to mitigate vulnerability.**

8 Benefits of the Ground Improvement Programme (GIP)

The benefits of the GIP are:

- The Science Trial results has enabled MBIE to update its guidance document for designing and undertaking residential ground improvement in Canterbury with a wider range of ground improvement options
- The MBIE guidance has been revised and issued with advice for the repair or rebuild of foundation damage during the CES. All ground improvement methods included in MBIE's guidance are compliant with the New Zealand Building Code
- There are options for suitable and practical ground improvement designs and construction techniques for residential properties (integrated foundation solutions)
- Refinements have been made to ground improvement construction methods in Canterbury to ensure high quality and consistent results
- For many sites MBIE-endorsed ground improvement solutions are now more affordable than TC3 shallow foundation solutions
- Streamlined consenting processes for residential ground improvements, reducing costs and administration
- MBIE endorsement of additional shallow methods of ground improvement for cleared sites has opened up the market for smaller, non-specialised contractors
- Reinforced soil-cement rafts and reinforced gravel rafts at shallow depths can now be constructed by a large number of contractors without the need for investment in specialist equipment, whereas stone columns and driven timber poles require more specialised equipment and labour
- A standard specification is being developed by a panel of consultants and contractors working with the New Zealand Geotechnical Society and MBIE. The aim is to enable more efficient design, streamline the pricing, materials production, and overall quality of ground improvement work
- There is greater flexibility for rebuilding on residential land, including:
  - More affordable ground improvement options for property owners that would prefer to improve the ground performance of their property, rather than building a TC3 surface structure foundation, which ensures good building performance but may require re-levelling in future events and does not improve land performance
  - Ground improvement and TC2 foundation combinations (integrated foundation solutions) allow a wider range of cladding and roofing systems, compared to TC3 surface structure foundation options with no ground improvement, which can limit the cladding and roofing systems available (based on MBIE guidance).

KEY POINTS

Benefits of the GIP

1. **Results from the GIP have made a key contribution to the 2015 update of the MBIE guidance for repairing and rebuilding structures on TC3 land in Canterbury.**
2. **As a result of data from the Science Trials, MBIE has endorsed more affordable ground improvement solutions to mitigate risks of land vulnerable to liquefaction.**
3. **A standard specification is being developed in collaboration with MBIE and New Zealand Geotechnical Society industry panels to enable more efficient design, tender and execution of ground improvement works on residential sites.**
4. **Canterbury contractors have upskilled so they can use a wider range of cleared site ground improvement methods.**

9 Summary and Conclusion

The GIP is a world-leading research project that has advanced global knowledge and understanding of appropriate ways to improve the performance of land vulnerable to liquefaction damage. The EQC and T+T worked with leading experts from New Zealand and overseas. The GIP has identified and verified the performance of simple, practical and affordable methods to strengthen and/or stiffen the upper surface soils (the non-liquefying crust) to reduce the damaging effects caused by liquefaction of underlying soil layers.

The GIP included:

The Ground Improvement Science Trials

Physical works were undertaken in three phases between April and December 2013. Throughout 2013 and 2014, data from the Science Trials was assessed, reported on and internationally peer reviewed. Tested methods included:

- Rapid impact compaction
- Geopier Rammed Aggregate Pier™ System
- Driven timber poles
- Low mobility grout
- Resin injection
- Reinforced gravel raft
- Reinforced soil-cement raft
- Permeation grouting (construction trial only – method was unsuccessful and therefore not tested)
- Horizontal Soil Mixed (HSM) beams (experimental new method for existing houses) but has potential limitations and constraints.

The Pilot

The primary objectives of the Pilot were to:

- Determine the costs, practicalities and risks associated with constructing the best-performing ground improvement options, identified by the Science Trials, constructed in an actual residential setting
- Assess Canterbury contractor capability to implement ground improvement solutions and stimulate the market
- Enhance understanding and acceptance by other key stakeholders.

The types of ground improvement works piloted were: geogrid reinforced gravel raft, in-situ mixed soil-cement raft, geogrid reinforced ex-situ mixed soil-cement raft, stone columns, driven timber poles and HSM beams.

Prior to the completion of the GIP, and subsequent 2015 update of the MBIE guidance, ground improvement solutions for residential properties were relatively expensive and not widely adopted in Canterbury. Understanding and acceptance of ground improvement among recovery stakeholders and those interested in building houses on liquefaction-vulnerable land was required for the implementation of proven ground improvement solutions but also to facilitate a more holistic approach to the Canterbury recovery in relation to land and building damage. Stakeholders included: property owners, insurers, regulatory authorities, design, engineering, and construction professionals.

All of the following outcomes can be attributed to positive working relationships with recovery stakeholders:

- Regulatory revision of ground improvement guidance
- Increase in contractor capacity and capability for cleared site residential ground improvement

- Rigorous testing during the Science Trials and the Pilot of the GIP has identified the limitations of each method, increasing the engineering and contractor understanding of ground improvement and improving quality assurance standards
- Simplified or streamlined consenting requirements for ground improvement works on residential properties, including those which may require contaminated land testing related to historical land use or listed on the Hazardous Activities and Industries List (HAIL)
- Refinements by Canterbury contractors to their construction methods to ensure high quality and consistent results and improved health and safety procedures
- Development of a standard specification to promote a more consistent approach to the construction of ground improvement works in Canterbury and the wider industry
- Working with recovery agencies, community facilitators, regulatory authorities, engineers, insurers and their project managers, contractors and property owners during the Pilot has provided a greater understanding of the complexities in undertaking ground improvement works and the potential issues with the end-to-end process for a customer's rebuild.

The results of the GIP are not only relevant to the Canterbury recovery but also to other residential areas in New Zealand and around the world that are vulnerable to liquefaction damage.

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