Ground Improvement Programme

Horizontal Soil Mixed Beams

Proof of Concept Pilot Summary Report

Version 1.0

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Report prepared by Stretton Consulting and the Earthquake Commission

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1 EXECUTIVE SUMMARY

The Ground Improvement Programme (GIP) is an Earthquake Commission (EQC) led, internationally collaborative research programme that informs affordable and practical ways of making residential land less vulnerable to liquefaction.

The GIP is divided into two main work streams:

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

The Science Trials developed, tested and verified shallow ground improvement methods in the residential red zone, which can be used to strengthen residential land vulnerable to liquefaction. The Pilot applied Science Trial learnings to residential properties to determine the market costs and practicalities associated with various methods. The GIP developed residential ground improvement methods for both 'cleared sites', where the houses have been demolished or removed, and 'occupied sites', where the houses remain in place.

This report focuses on the Proof of Concept Pilot (PoC) for horizontal soil mixed (HSM) beams, a ground improvement method developed during the Science Trials for occupied sites. The PoC aimed to assess the indicative costs and practical applicability of the HSM method in a residential setting, to determine whether further investment would benefit the Canterbury Recovery.

Currently it is understood that the HSM method is the only proven ground strengthening method identified to date that can be constructed on liquefaction vulnerable land without the need to demolish or temporarily relocate the house.

Over a period of five months in 2014 HSM beams were installed under three green zone houses in Christchurch. While this work demonstrated that HSM beams can be practically installed beneath residential houses, there are various technical constraints that can limit the number of properties to which the method can be applied. These constraints include:

- A requirement for a water table depth of 0.9m below the ground surface, with shallow foundations at least 0.5m above the water table
- A requirement for adequate clearance from the house to the property boundary both above and below the ground.
- The risk of minor damage to paved surfaces, interior linings and concrete ring beams caused by low levels of ground heave during the HSM beam installation process.

Currently only one contractor has the experience and specialised equipment necessary to install HSM beams. As a result of the PoC, five contractors now have some knowledge of the 'two-way drilling/mixing' method and have indicated that they would be prepared to look at pricing HSM beam work under TC3 zoned single dwellings, if this work were to be tendered competitively.

Based on PoC observations, HSM beam installation costs for a typical house are likely to range from $110,000 to $140,000 excluding GST. It is estimated that the HSM method can technically be applied to around 30% to 40% of liquefaction vulnerable properties; however, the costs of the HSM method are likely to make it unaffordable or undesirable in most cases, once engineering, project management, consenting and enabling works' costs are also considered.

Economies of scale were not explored because multi-unit properties (complexes containing more than two buildings, otherwise referred to as MUBs) suitable for HSM beam installation and featuring four or more houses, could not be found. Lack of suitability was mainly for technical reasons (high water tables, boundary proximities, buried council services, heritage trees).

The future development of bespoke technology, such as a retractable mixing head tool or automated grout injection, may improve the productivity of the method, lower the costs and improve the number of properties to which the method can be applied. Owing to the uncertainty associated with product technology development in terms of time and cost, the development of the retractable mixing head tool has been suspended by EQC and is only partly complete.

The practicality of installing HSM beams on single dwelling properties, with adequate space, shallow foundations and water table depths greater than 0.9m below ground level, has been proven and the method could potentially be used for land repairs beneath some repairable houses in the future. The uncertainty of technology development and the time it would take to develop a contractor supply market mean that it is unlikely to be commercially viable in time for the Canterbury Recovery.

The purpose of this report is to summarise the technical learnings, indicative costing information, market development and anticipated applicability of the HSM method.

2 BACKGROUND

2.1 Ground Improvement Programme

The Canterbury earthquakes of 2010-2011 demonstrated the significance of liquefaction vulnerability and the extent to which liquefaction can exacerbate damage to buildings and land. In Canterbury liquefaction-induced damage accounted for a third of the total cost of the recovery.

Liquefaction across Canterbury caused the ground surface in many areas to subside and in some cases this increased the vulnerability of the land to the damaging effects of liquefaction. Increased liquefaction vulnerability (ILV) is a form of EQC compensated land damage where the land has become more vulnerable to liquefaction-induced land damage in a future earthquake.

After the Canterbury earthquakes an estimated 17,000 green zone properties in Canterbury were vulnerable to liquefaction. Many of these properties had houses that required foundation repairs or rebuilding.

Building houses on liquefaction vulnerable land requires expensive and robust foundation systems. This enables the buildings to meet acceptable standards of earthquake resilience but does not improve the ground condition. While ground improvement methods exist, these have been for large-scale commercial builds; they are often too expensive and impractical for small residential sites.

The EQC under its research mandate initiated the Ground Improvement Programme in 2013 to:

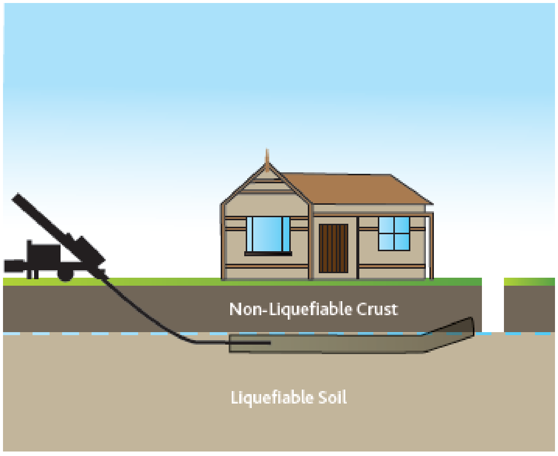
- Identify, develop and verify affordable ground improvement methods for use on residential land to reduce the damaging effects of liquefaction
- Encourage a more holistic approach to building on liquefaction vulnerable land – considering both land repair and structural foundation solutions in the design process
- Assist in the early adoption of ground improvement in Canterbury
- Facilitate building regulator acceptance of residential shallow ground improvement methods
- Determine consenting requirements and where possible work with council to streamline consenting processes for residential ground improvement
- Assess and establish Canterbury contractor capabilities, ensuring adequate numbers of suitably experienced contractors are available to carry out the works
- Improve the national and international understanding of residential liquefaction mitigation strategies.

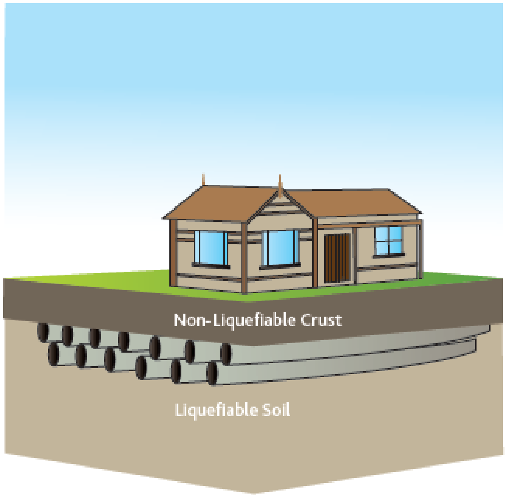
The Science Trials began in April 2013 in the red zone, to test and verify the effectiveness of a number of residential ground improvement methods that could be constructed in typical Canterbury soils. There were various commercial scale options that could potentially be adapted for residential application on cleared sites (new sections or where houses have been removed). Six methods were tested, of which five were successful. Four solutions (gravel rafts, cement stabilised rafts, stone columns and driven timber poles) were piloted on 29 green zone residential cleared sites to assess the affordability and practicality of these methods.

Very few ground improvement methods existed for commercial sites where the building remains in place. Cement-based permeation grouting, a non-destructive ground improvement method used overseas for specialist commercial applications, was attempted. However, test panels could not be constructed in the typical fine grained Canterbury soils present at the site. In the absence of an alternative, a new non-destructive method, HSM beams, was developed that proved effective in mitigating liquefaction vulnerability by creating a stiffer and thicker crust.

2.2 Horizontal Soil Mixing

The HSM method mixes injected grout with soil beneath the house to form two horizontal rows of 500mm diameter cylindrical beams. The beams are horizontally spaced 500mm apart; the lower level beams are placed directly below the non-treated soil spaces between the upper layer beams, as per the diagram below. Installation occurs within the subsurface soils to stiffen and thicken the non-liquefying crust beneath the house. Directional drilling equipment is used to create a borehole under the length of the house to an excavated trench at the opposite end, where a 500mm diameter mixing tool is attached to the drill rods. Grout is then injected through the drill rods to the mixing tool and mixed back with the soil to form a beam of cement-stabilised soil. This 'two-way drilling/mixing method' of installing HSM beams typically requires around 4m of clearance behind the house to accommodate the treatment area that extends beyond the house footprint and the excavated trench to attach the mixing tool. The HSM beams proved successful during the Science Trials in both silty and sandy soils.





2.3 Proof of Concept Pilot

The Pilot projects were undertaken to encourage a market for ground improvement and to determine the practical implications and affordability of each method and the availability of experienced contractors. The cleared site shallow ground improvement methods were adapted from commercial scale examples, and experienced contractors were available to tender competitively for Pilot contracts. The HSM method was new and experimental; it required further technical development and socialisation of the method among contractors before a full tendered Pilot was possible.

The PoC was undertaken to assess and develop the method to determine whether it could be commercially viable in time for the Canterbury recovery.

The objectives were to:

- **Prove the practicality of the method in a residential setting** – HSM beams were constructed on cleared sites and then beneath two houses during the Science Trials. As these properties were earthquake damaged and awaiting demolition, many of the practicalities associated with construction needed to be determined. These included space constraints for equipment, the likelihood of underground obstructions and the effects of the installation process on foundations and the house. Vertical ground heave during the installation process was of particular concern, as any cracking on internal linings or perimeter concrete ring beams could reduce the affordability of the method or be undesirable for fully repaired houses. An assessment of the practical constraints would provide an indication of how widely the method could technically be applied
- **Socialise the method to increase the contractor supply market** – Other contractors would be invited to observe and learn the HSM beam installation process in order to price competitively tendered contracts in the future if needed
- **Develop HSM beam installation technology** – It was identified during the Science Trials that specialised equipment could be developed to reduce the cost of HSM beam installation and widen its applicability. This specialised equipment included a retractable mixing head tool and different (and possibly more powerful) drilling and grout mixing equipment, linked together by automation. A retractable mixing head tool would remove the need for an excavated receiver trench and allow the beams to be mixed back continuously without breaking the surface. Automated grout injection would likely improve quality assurance and the speed of installation
- **Gain indicative costs** – Constructing HSM beams under single and multi-unit buildings MUBs would indicate the potential affordability of the method.

3 SINGLE UNIT DWELLINGS

HSM beams were installed under three liquefaction vulnerable houses in the green zone, using the two way drilling/mixing method with manually controlled grout injection. Owners relocated to temporary accommodation while the HSM beams were installed, primarily because their sewer, water, power and telephone services needed to be disconnected to enable the construction.

3.1 Property Details

The locations and details of the three properties were as follows:

Property	Bower Avenue, New Brighton	Landy Street, Dallington	Southey Street, Sydenham
Description	Single storey, perimeter concrete ring beam foundation, timber subfloor, timber framing and weatherboard cladding, lightweight roof	Single storey, perimeter concrete ring beam foundation, timber subfloor, timber framing with brick cladding, lightweight roof	Single storey, perimeter concrete ring beam foundation, timber subfloor, timber framing and weatherboard cladding, lightweight roof

Repair State	Existing unrepaired earthquake damage to interior wall linings	Existing unrepaired earthquake damage	Fully repaired dwelling. Decorative reinforced concrete driveway
Soil Type	Sandy	Silty sand	Silty sand
Number of Beams	28	27	27
Length of Beams	38m	23m to 27m	32m to 33.5m

3.2 Technical Observations

- **Water table depths** – The water table depths at the three properties ranged from 1m to 1.2m below the ground surface. HSM beam installation requires the top of the upper level of the beams to sit just clear of the water table. The water table depths typically need to be at least 0.9m below ground level (assuming the ring beam and pile foundations are no more than 0.4m deep). This is required to minimise the risk of beam construction damaging the overlying foundations (see also 'Ground heave and consequential damage' below).
- **Underground obstructions** – One of the risks identified at the beginning of the project was the potential for the mixing tool to become jammed on an obstruction, resulting in an incomplete beam under the house. The contingency plan in this event was to install additional beams directly either side of the incomplete beam. This plan was never trialled as no significant underground obstructions were encountered on any of the Pilot properties.
- **Soils conditions encountered** – HSM beam drilling in and mixing back were achieved on all three sites using the same Ditch Witch 20/20 drill rig used during the Science Trials. The design anticipated a mixing pull back speed of 1m/min. This was fairly consistently achieved, although slower pull back speeds of 0.5m/min were required in a few instances to maintain cement soil mixing consistency in areas where the soils were dense.
- **HSM beam installation rates** – The average beam installation rate was 2.5 beams per day, or 11 days of drilling and mixing on each site, with the site crew working 12 to 13 hour days. A peak installation rate of four beams per day was achieved for two days on each of the three sites, but factors such as encountering areas of hard ground and equipment breakdowns and maintenance (e.g. blown drill hydraulic hoses) lowered productivity. It is interesting to note that although the beam lengths differed between sites (ranging from 23m to 38m), the same 2.5 beams per day average installation rate was achieved. It appears the set-up times for drilling and mixing influenced beam installation rates more than beam length variations. It should also be noted that the site crews worked 12 hour days to achieve the production rates listed above; these long hours are not considered sustainable long term.
- **Construction periods** – Construction work took between four and seven weeks for each property. While there were only 11 days of consecutive drilling and mixing involved, the remainder of the time was required for initial set-up and reinstatement after the HSM beam installation was completed.
- **Drilling accuracy** – Drilling beneath the ground where the house structure interrupts the line of sight between the locator and the drill head requires the use of a 'remote locating' system. For the PoC, a DigiTrak F5 locator tool was set up at the other side of the house, projecting an electronic signal to a screen on the drill rig. With the tight tolerances specified for the drill string alignment (plus or minus 50mm), the drill operator's ability to achieve these tight tolerances while drilling with the remote

locator system was crucial, and a factor that limited drilling speed and HSM beam installation rates. Only one drill operator on site was experienced enough to achieve the required tolerances consistently using the remote locator system. The expected productivity gains related to the use of a retractable mixing head tool (in development) will still be limited by the drill operator's ability to use a remote locating system.

    - **Reinforcement bar interference with drilling accuracy** – Drilling beneath a reinforced concrete driveway at the Southey Street property revealed a limitation of the DigiTrak F5 when used in 'remote locating' mode. The reinforcing bars within the reinforced concrete driveway caused interference between the drill head 'sonde' and the locator unit at the ground surface, resulting in misalignment. The alignment issue in this instance was corrected by using the 'walkover locating' mode to allow correct steering of the drill head. In future, more sophisticated locating equipment may be required when drilling beneath reinforced concrete floor slabs (e.g. drill head 'sonde' connected to the drill rig by wire down the centre of the drill rod string).

- **Ground heave and consequential damage** – Between 2mm and 5mm of vertical ground heave was detected by surveyors as HSM beams were constructed beneath the perimeter concrete ring beams of each house. At one property the concrete driveway developed cracks, and at another cracks appeared on the concrete ring beam and in internal wall linings, incurring a repair cost of $6500 excluding GST. In general the ground heave appeared to rise and fall with the mixing head advancement. This may indicate that the ground heave was caused by the mixing function rather than the addition of grout volume. Further testing of the blade alignment variations on the mixing tool may reduce ground heave and consequential damage to house foundations or linings. Lower volumes of grout could also be explored; however, an automated grout injection system would be needed.

- **Noise and vibration levels** – Noise and vibration were monitored on all three sites during construction. One complaint was received, from a neighbour directly adjacent to the Bower Avenue property. Monitoring at the time showed that the noise and vibration levels were well below resource consent thresholds.

- **Working from the street** – At the Southey Street property the drilling and grout mixing equipment was positioned on one lane of the road carriageway due to space constraints within the property. There were no issues with grout spillages, and no grout wash-down from the site into the street stormwater system occurred.

- **Council and services authorities –** All the required notifications were provided to Christchurch City Council to advise that the work was underway, but no inspections were undertaken by Council personnel. A 'Consent to Work near Conductors and Equipment of Overhead Electric Lines' was issued by Orion. An Orion representative visited the Southey Street site, where 11KV underground power cables had to be exposed in the footpath, and was satisfied with the drilling and mixing technique in close proximity (150mm) to Orion's live power cables.

- **Enabling works and extent of reinstatement –** The use of the two way drilling/mixing method required substantial enabling works (demolition and/or reinstatement) on two of the properties (concrete block garage demolished at Landy Street, and coloured patterned concrete driveway removed and reinstated at Southey Street). The retractable mixing head tool (once fully developed) will obviate the need for excavated trenches to attach the mixing head tool, saving the cost of demolishing and reinstating garages, paved surfaces, landscaping features and lawns etc. Underground services, however, such as sewer, stormwater, potable water and telephone services, will still require exposure through trench excavation and will need reinstatement after HSM beam installation. Where possible, reinstating existing services to avoid paved surfaces and landscaping features will be key to reducing reinstatement costs.

3.3 Pilot Construction Costs

The total construction cost for each site ranged from $237,000 to $291,000, excluding GST, depending on treatment area size and the extent to which enabling works were required. A comparison of construction costs for the three properties is shown in the table below:

Property	Treatment Area a	Final Construction Cost b	$/m² c=b/a	Site Specific[1] and Contractor Specific[2] Costs d	Total Cost Excluding Site[2] and Contractor Specific[3] Costs e=b-d	$rate/m² f=e/a
Bower Avenue	532m²	$291,000	$547/m²	$36,000	$255,000	$479/m²
Landy Street	344m²	$237,000	$689/m²	$51,000	$186,000	$540/m²
Southey Street	442m²	$287,000	$649/m²	$66,000	$221,000	$500/m²
Average	**439m²**	**$271,666**	**$618/m²**		**$220,666**	**$502/m²**

Notes:

1 **Final construction** – The total construction cost for HSM beam installation after the contractor's final claim.

2 **Site specific costs** – Enabling works' costs specific to a particular site included the garage demolition at Landy Street ($15,000), and the decorative concrete driveway replacement at Southey Street ($30,000).

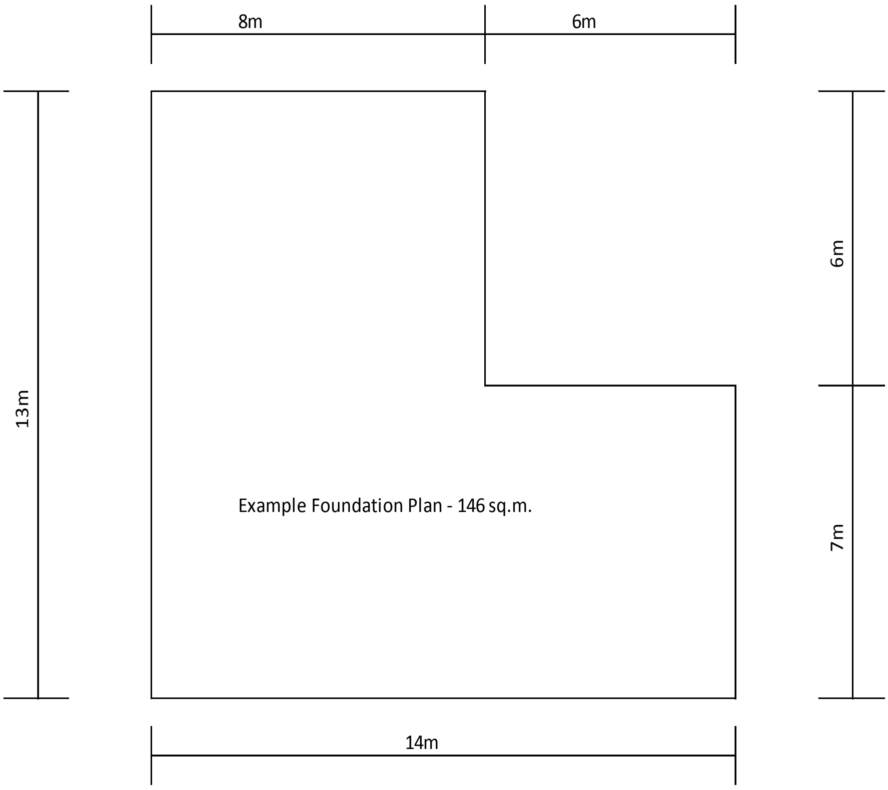
3 **Contractor specific costs** – Accommodation and transport costs for the Auckland-based site personnel working on the project, averaging $21,000 per site, and $15,000 solution development fee, totalling $36,000 for each site.

4 All costs exclude GST, are indicative and were collected from contracts undertaken in 2014.

As can be seen in the table above, the average cost for 439m^2 of treated area on a property reduces to $220,666 once site specific and contractor specific costs are deducted. This corresponds to an average rate of $502/m^2.

4 INDICATIVE HSM BEAM CONSTRUCTION COSTS

The Ministry of Business, Innovation and Employment's (MBIE) representative floor plan of 146m^2 (refer to sketch below for details) has been used to size a typical single unit house for calculating an indicative construction cost. The Science Trials report recommends a treatment area of the house footprint plus a buffer 2m beyond the front and back of the house, and 1m either side of the house.



The treatment area would therefore cover:

House footprint	$146m^2$
Buffer (minimum extensions to beams – 2m back and front, and 1m sides)	$90m^2$
2m long mixing head receiver pit/beam at back	$32m^2$
Total	**$268m^2$**

At an average construction cost of $\$502/m^2$, the total cost of treating $268m^2$ would be $134,536 excluding GST.

It is therefore considered that the construction costs for a standard treatment area ($268m^2$) could range from $110,000 to $140,000 excluding GST. The lower $110,000 figure applies where drilling can be performed within the site, so saving on the costs of reinstating the road, footpath and underground services.

It is estimated that the total construction cost could be lowered, in consultation with the contractor, if:

- The retractable mixing head tool is successfully developed and HSM beam daily installation rates increase from 2.5 beams per day to an expected 3.5 beams per day
- Grout mixing quality assurance is achieved through automated grout injection (a reduction of one labour unit)
- The cost of an externally contracted site engineer is removed
- A market develops and contractors bid competitively for the work
- Economies of scale are achieved through coordinating group repairs for MUBs or single dwellings.

However, it is acknowledged that these potential cost reductions are speculative at this time and have yet to be tested in practice. The indicative rate and expected construction costs do not include costs that would normally be incurred in undertaking works, such as professional fees (engineering, design, project management and legal), consenting fees, and enabling works. Considering these additional costs, it is likely that the HSM method would not be economically viable for many properties.

5 MULTI-UNIT BUILDINGS

T+T and EQC investigated more than 400 MUBs on liquefaction vulnerable land to identify buildings that could benefit from HSM beam installation. EQC indicated that for the purposes of the PoC, four or more units would be preferred to determine the potential costs for larger sections. No MUBs were identified as suitable. Some were technically viable but unsuitable due to the complexity of coordinating multiple owners (the presence of an uninsured house or not all owners wishing to participate). Technical reasons included: high water table elevations above the 0.9m threshold; boundaries too close to houses to achieve the recommended treatment areas; and the presence of buried council services or heritage trees.

6 RETRACTABLE MIXING HEAD TOOL DEVELOPMENT

EQC provided development funding for a prototype retractable mixing head tool to allow HSM beams to be constructed from one side of a property or from the road. If successful, this would reduce the costs of enabling works and increase the number of properties where the method could be practically undertaken (many properties do not have the 4m clearance between the houses and the property boundaries required by the two way drilling/mixing method).

Version one of the prototype retractable mixing head tool was tested in a seven day period in the residential red zone. Unfortunately testing showed that the tool was not able to construct HSM beams reliably and consistently to the minimum 500mm diameter required. The costs of developing version one and testing in the red zone totalled $142,000 excluding GST. A reconfigure of the tool was considered. However, it was decided that further investment in the tool would not be pursued until the wider applicability of the HSM method was able to be assessed.

7 DEVELOPING CONTRACTOR CAPABILITIES

Five contractors were approached to observe the HSM beam installation process with the intention of enabling pricing of future HSM beam work. Four contractors visited the Southey Street site to talk to the construction team and witness HSM beams being installed under the house. Each of these contractors indicated they would be prepared to look at pricing HSM beam work under single unit houses if this work were tendered competitively by EQC.

8 APPLICABILITY

T+T has indicated that there are approximately 17,000 liquefaction vulnerable properties in Canterbury. Many of these properties, if damaged in the earthquakes, will be occupied sites or have repairable houses.

The technical viability of installing HSM beams beneath houses on liquefaction vulnerable properties is dependent on the following constraints:

- **Depth to the water table** – If the water table is more than 0.9m below ground level, there is a high risk of the HSM beams clashing with existing foundations during installation

- **Distance to the property boundary at the front and rear of the house** – There needs to be at least 2m between the property boundary and the front and back of the house's external walls (adjacent to the beam orientation) for the HSM beams required beyond the house footprint
- **Distance to the property boundary at the sides of the house** – A minimum 1m clearance is required from the external house walls (parallel to the beam orientation) to the property boundary for the required treatment area beyond the house footprint
- **Council buried services (storm water and sewer etc.)** – These need to be located outside the HSM beam treatment area
- **Heritage trees** – Heritage trees and their roots need to be located outside the HSM beam treatment area. Similarly, the roots of significantly large trees that are not protected could affect the ability to construct HSM beams (although this has not yet been thoroughly tested).

To get an indication of the practical applicability of the method to liquefaction vulnerable green zone properties, the EQC ILV portfolio was investigated to get a best guess estimate. Of the estimated 5,000 green zone ILV properties in Canterbury, 80% are likely to be occupied sites with repairable houses in place (4,000). Based on the technical constraints listed above, T+T estimates that approximately 30% to 40% (1,200 to 1,600) of green zone ILV occupied sites may be practically suited to having HSM beams installed.

Further developments to reduce some of the technical constraints of the method may increase the number of properties to which the method could be practically applied and reduce construction costs. However, due to the relatively low number of properties likely to be able to benefit from this new system and its relatively high costs, it was decided that the HSM method should not be explored further at this time.

9 CONCLUSION

The PoC was undertaken to assess and develop the new method to determine whether it could be commercially viable in time for the Canterbury Recovery.

To assess the commercial viability of the HSM method, the PoC aimed to:

- Prove the practicality of the method in a residential setting
- Socialise the method to increase the contractor supply market
- Develop HSM beam installation technology
- Gain indicative costs.

To date HSM beams have been successfully installed under dwellings on three green zoned, single unit properties, using the two way drilling/mixing method with manually controlled grout injection. This has demonstrated that HSM beams can be practically installed beneath residential houses, with the following technical observations highlighted:

- The design constraint of a minimum water table depth of 0.9m meant that HSM beams were installed low enough to ensure the dwelling foundations were not struck. This constraint significantly limits the number of liquefaction vulnerable properties to which the method can be applied. Further HSM beam installation work would be needed at raised water table elevations to assess the risks.
- Ground heave of between 2mm and 5mm caused minor damage to paved surfaces, interior linings and concrete ring beams at each site. Although the costs to repair were not significant, damage of this kind may deter owners of fully repaired houses. Further testing work on realigning the blade

orientation on the mixing tool or automating the grout injection may reduce the ground heave and consequential damage repair costs.

- Set-up times for drilling and mixing influenced beam installation rates more than beam length variations. A peak installation rate of four beams per day was achieved for two days at each site; areas of hard ground and equipment breakdowns and maintenance lowered productivity to 2.5 beams per day, with site crew working 12 to 13 hour days, which may not be sustainable long term.
- Faster drilling speeds will likely improve beam installation rates. A drill operator's ability to use the remote locator system to achieve the specified drill string alignment is crucial and likely to improve HSM beam installation rates more than increasing the power of the drill rig.
- The DigiTrak F5 remote locator system was not able to be used when mixing under a reinforced concrete driveway. Drilling beneath reinforced concrete floor slabs in the future may require more sophisticated locating equipment to be used (e.g. drill head 'sonde' connected to drill machine by wire down drill rod string).
- The retractable mixing head tool, once developed (intended to increase production rates and therefore reduce overall costs), will still require existing services within the property boundaries to be reinstated at completion. Realigning these services around driveways and landscaping features during reinstatement may minimise costs.

The economic benefit of coordinated repairs under MUBs was not able to be tested because suitable properties with four or more houses could not be found due to technical reasons (high water tables, boundary proximities, buried council services, heritage trees), insurance reasons or owners not wanting to participate.

It is estimated that the HSM beams may be technically viable for 30% to 40% of liquefaction vulnerable properties. The practicality of installing HSM beams on single dwelling properties, with adequate space, shallow foundations and water table depths greater than 0.9m below ground level, has been proven and the method could potentially be used for land repairs beneath some repairable houses in the future if required.

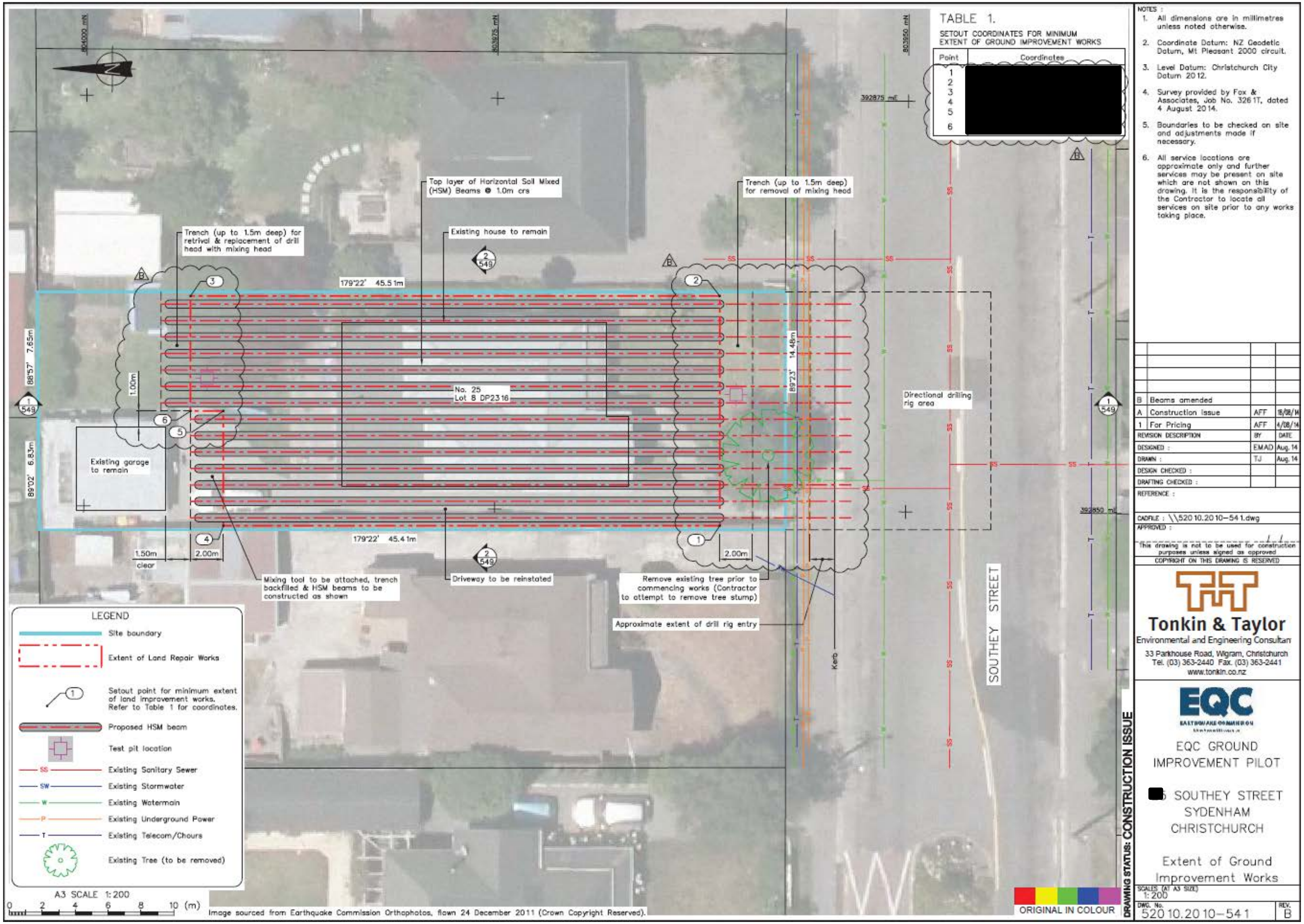
Currently only one contractor has the experience and specialised equipment necessary to install HSM beams. Owing to the PoC, five contractors now have some knowledge of the 'two-way drilling/mixing' method and have indicated that they would be prepared to look at pricing HSM beam work under TC3 zoned single dwellings, if this work were to be tendered competitively.

The development of the retractable mixing head tool is only partly complete. Owing to the uncertainty associated with product technology development in terms of time and cost, EQC has suspended funding until the commercial viability of the HSM method for the Canterbury recovery has been determined.

The average HSM beam construction cost for the PoC properties was \$502/m^2 excluding GST, once contractor specific and site specific costs were removed. Applying this rate to a typical treatment area (based on a MBIE representative floor plan) of 268m^2 would therefore equate to \$134,536 excluding GST. It is estimated that the HSM beam construction cost for a typical house is likely to range from \$110,000 to \$140,000 excluding GST, depending on whether drilling in from the road is required. These costs are likely to make the method unaffordable or undesirable in most cases, especially once engineering, project management, consenting and enabling works' costs are added.

Once the retractable mixing head tool is developed, a market develops, contractors bid competitively for the work, and group repairs can be coordinated, the HSM method could be a commercially viable option for strengthening liquefaction vulnerable land after an earthquake event. The uncertainty of technology development and the time it would take to develop a contractor supply market mean that it is unlikely to be commercially viable in time for the Canterbury recovery.

Appendix A – Typical HSM Beams Layout Drawing



Appendix B – Typical HSM beam Long Section and Cross Section