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Resin injection for liquefaction mitigation of an existing waste water treatment plant, Seaview, Wellington, NZ

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ABSTRACT

As part of the Wellington Water Ltd Seismic Strengthening programme, the Seaview Waste Water Treatment Plant (WWTP) Pump Station and Milliscreen Buildings required Serviceability Limit State (SLS2) performance to be during a 1:500 year earthquake.

The sewage for the Hutt Valley passes through the Milliscreen (as it enters the treatment plant) and Pump Station (high pressure outfall to Pencarrow) as part of the sewerage treatment process (for approximately 100,000 people). Failure of either building would result in overflow to the Wellington Harbour.

Detailed serviceability criteria was provided by the structural engineer regarding the performance level of the foundation systems during the design level earthquake to maintain operation.

A detailed geotechnical investigation was completed of the site to assess the risk of liquefaction and liquefaction related damage. It was found that during the SLS2 event building damage was likely to exceed the criteria provided.

A range of options were considered for ground improvement beneath the existing structure, including traditional piles, jet grouting, permeation grouting, bio-calcification, and resin injection. Due to a range of technical issues, building access, and fiscal limitations, resin injection methodology presented by Mainmark was chosen as the preferred option.

This paper presents the detailed design, verification works, construction supervision and quality control for the selected resin injection approach utilised by Mainmark.

1 INTRODUCTION

Coffey Services (NZ) Ltd were engaged by Wellington Water Ltd to assess the risk of seismic induced damage to the Pump Station and Milliscreen buildings at the Seaview Waste Water Treatment Plant, Lower Hutt, Wellington.

The selected ground improvement method was required to achieve satisfactory performance as per the design tolerances specified by the client, an extract of which is provided in Section **Error! Reference source not found.** below, at the following design earthquake levels.

- 100% NBS for SLS1 & SLS2 based on the structures being importance level (IL4) with a design life of 50 years.

For the ULS design case prevention of collapse is required. Specific Damage Criteria was not set.

- 55% of the New Building Standard (NBS) for ULS based on the structures being importance level (IL4) with a design life of 50 years.

1.1 Performance Criteria

The following table provides an extract of the critical design tolerances following an assessment completed by the structural engineer, client and WWTP operators.

Table 1: Extract of design tolerances for Pump Station and Milliscreen Buildings

	SLS1 Criteria	SLS2 Criteria
Maximum out of level over the whole of each building	10mm	200mm
Local floor slope	1 in 500 (2mm/m)	1 in 100 (10mm/m)
Differential Settlement between machine plinths and adjacent slab.	1mm	5mm
Steps at joints or cracks in slabs and walls	1mm	10mm
Depth of liquefaction ejector entering building	Nil	50mm

2 SITE LAYOUT

The site is nearly level with only small, localised rises or falls across the site, and predominantly covered in hard standing including asphalt or concrete surfaces. Some minor areas of grass are present.

Inside, the milliscreen plant the area is broken into two levels. The milliscreens are located on the upper level, and the lower (ground floor) level comprises a range of uses (see photo below), from pipes, pumps to an open workshop area at the western end.

The pump station building can be split into three main areas: transformer bay, main pump room (see photo below) and a wet well.



Figure 1: Photos of the Pump Station & Milliscreen Buildings (Milliscreen – Left, Pump Station – Right)

During the initial assessment and design process it was identified that due to the extremely restricted access to parts of the buildings, early contractor engagement would be critical.

3 SITE GEOLOGY

The site is underlain by Reclamation Fill overlying Marginal Marine Sediments. At depth, the site is underlain by the Hutt Aquiclude and the Hutt Aquifer.

Table 2: Soil Profile Summary

Depth (m)	Thickness	Project Unit	Design N60	Shear Wave	Φ'	c'	Young's Modulus E_v' (MPa)
Top	m			m/s	°	kPa	Design
0.0	2.5	Reclamation Fill	14	125	30	0	20
2.5*	1.0/3.2	Marginal Marine – Gravel	32	220	36	0	48
3.5/5.7	4.3/6.5	Marginal Marine – Sand	23	200	32	0	34
10.0	2.5	Marginal Marine – Silt	n/a	180	30	5	13
12.5	6.5	Hutt Aquiclude	n/a	200	30	10	9 (25 from 13.0m bgl)
19	-	Hutt Aquifer	n/a		40	0	100

Groundwater monitoring identified a level of 1.85m below ground level (bgl), with a design groundwater level of 1.5m bgl utilised in the assessments.

3.1 Site Seismic Response

The following Peak Ground Accelerations (PGA) were utilised in the design process:

- SLS1 – 6.2 M_{eff} , 0.09 PGA.
- SLS2 – 7.1 M_{eff} , 0.35 PGA.
- ULS – 7.1 M_{eff} , 0.34 PGA.

3.2 Previous Ground Motions

Ground motions experienced at selected sites near the WWTP during the Kaikoura (2016) Earthquake tabulated below.

Table 3: Ground motions during Kaikoura earthquakes

Site	Location	Peak Ground Accelerations (Kaikoura Nov 2016)	Site Subsoil Class	Distance from Site
SEVS	Seaview	0.19	D	1100m
LRSS	Randwick School	0.17	D	850m
LHUS	Lower Hutt Unilever	0.15	D	1200m

4 OPTION SELECTION

4.1 Tender Process

Following an initial assessment, it was identified that the design criteria would exceed the performance criteria and that some ground improvement would be required. It was preferred that the Hutt Aquiclude was not penetrated and therefore a ‘thickened crust’ solution was proposed. Utilising the concept of a thickened crust and the performance criteria, a performance specification was developed with an estimated depth of improvement to 6m bgl. The tender was split into Separable Portion 1 (Design) and Separable Portion 2 (Construction). Separable Portion 2 would only be awarded following completion of SP1, which included a verification trial and Detailed Design (both discussed below).

During the tender process, options for ground improvement included Jet Grouting, Bio-Calcification, and Resin Injection. Bio-calcification was not considered due to the lack of New Zealand experience and potential time frames for development/testing. Jet grouting, even with small rigs, was still limited to approximately 70% of the building footprint, with large critical areas inaccessible. Resin Injection (Mainmark) provided access to all areas, with enough existing data to allow for detailed design to progress.

5 DETAILED DESIGN PROCESS

Once the contract was awarded, the detailed design and verification process was completed. This section summarises the detailed design approach.

The ground improvement works and associated verification testing was assessed based on a relative improvement in behaviour across the site, using the Kaikoura earthquake (KE, 0.18g, 7.8M) event (November 2016) as a benchmark for expected ground behaviour.

There will be two key components to the design and verification of the ground improvements:

1. Simplified Assessment
2. Elastic Plastic Assessment

5.1 Simplified Assessment

The following steps were undertaken to complete the simplified assessment.

1. Liquefaction Assessment (Boulanger & Idriss, 2014) to refine the parameters PL and C_{fc} based on the Kaikoura earthquake event with the following maximum values assessed to a total depth of ~12 m:
2. Comparison of the fines content with the lab test data, the Probability of Liquefaction (PL) factor and the Fines Correction (C_{fc}) factor have a significant impact on the liquefaction and subsequent damage assessments.
3. Once the correction factors are addressed, post ground improvement target will be assessed as follows:
 - a. Modify the q_{c1N} value to reflect ground improvement.
 - b. Note: I_c & Fines Content (FC) % will remain the same as the pre-ground improvement profile. Typically, increasing q_c (tip bearing) value will reduce I_c and FC accordingly, often shifting silts and clays into a different soil classification, which would not be a true representation of the improvement.
 - c. Assess the post ground improvement profile for liquefaction using the SLS2 earthquake conditions and reassess against the following criteria:
4. Post Ground Improvement Criteria for an SLS2 event over the treated depth (minimum 6m). Liquefaction occurring below 6m is considered to have a low impact on the existing structures. The key to the post ground improvement criteria is the improvement of the treated zone to produce index values (as below) less than the KE during the higher SLS2 design event with a margin to act as a factor of safety.
 - a. Free Field Settlement < Settlement during the KE.
 - b. LPI < LPI during the KE.
 - c. LPI – Isihara < LPI-Isihara during the KE
 - d. LSN < LSN during the KE
 - e. CTL < CTL during the KE
 - f. Crust Thickness > Crust Thickness during the KE
5. Carry out a parametric assessment to assess the sensitivity of the ground improvement to varying improved depth and/or q_{c1Ncs} values.

It should be noted that the above assessment has limited capacity to directly assess building movement or damage against the structural damage criteria provided. It is a simplified solution and provides an overall comparison of the site pre-and post-ground improvement.

Reinforcement from the resin columns/planes was not considered in the design.

5.2 Parametric Assessment

To assess the appropriateness of the recommended 50% increase in q_{c1Ncs} , an assessment was completed by varying the % increase in q_{c1Ncs} against LSN and LPI over the treated thickness. There is a marked decrease in the reduction in index values with increase q_{c1Ncs} (see Figure 2 below).

Over the majority of the site, if q_{c1Ncs} is increased beyond 50/60%, there was a nominal improvement over the site's susceptibility to liquefaction.

Modifying treatment depth was also assessed, with the results producing a typically linear relationship between depth of treatment and reducing index values.

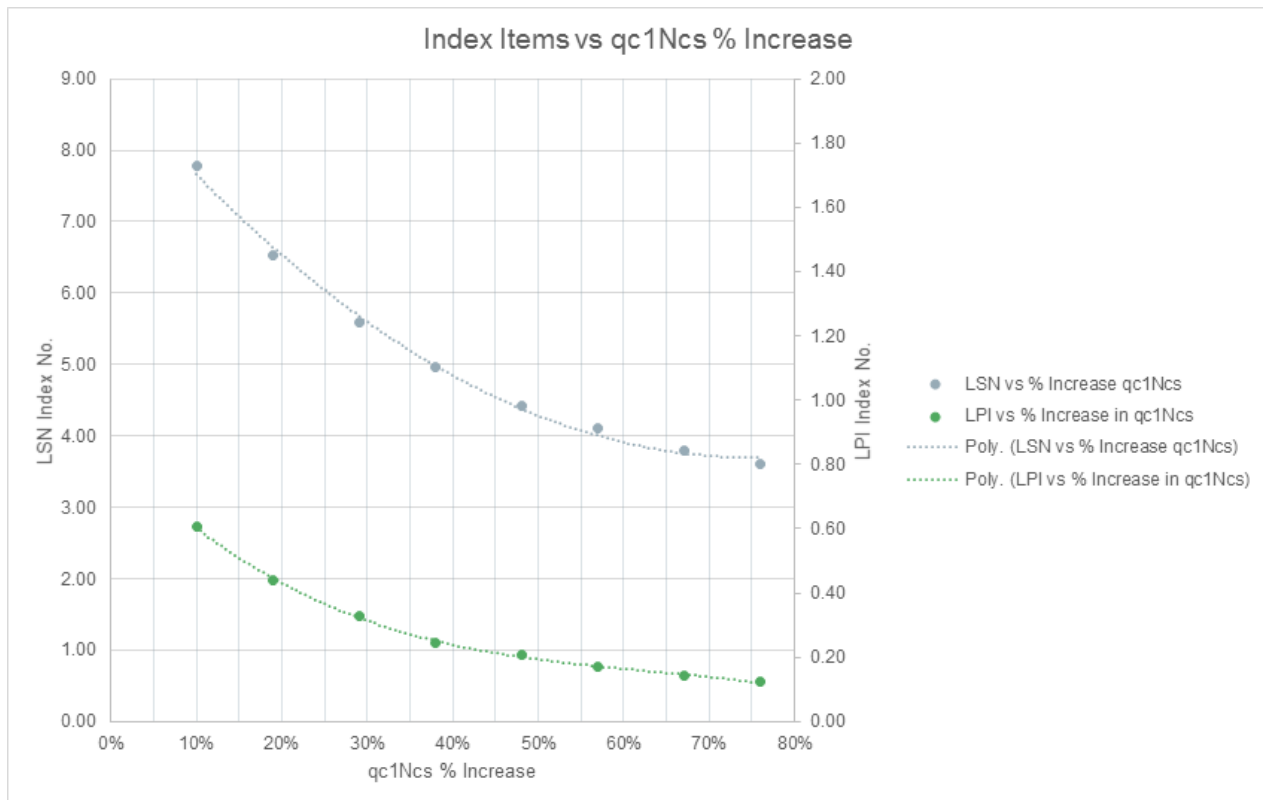


Figure 2: Liquefaction LPI & LSN vs q_{c1Ncs} % Increase

5.3 PLAXIS Model

The following section outlines the initial methodology to the Elastic-Plastic Assessment utilising Plaxis 2D.

The following general notes are made about the development of the profile and soil properties:

- An overall LPI was derived based on the post-treatment CPT results (see verification trial below).
- Stiffness reduction factor for liquefied soils applied to hardening soil young's modulus (E_{ref}^{50} , E_{ref}^{ur} and E_{ref}^{oed}) was based on the LPI and initial assessed at 0.16.
- The volumetric strain for the liquefied marine sand and marine silt layers was based on the liquefied marine sand and silt layers. Volumetric strain was utilised to assess the free field case.
- The micropiles modelled as Embedded Beam Rows (very high point loads in discreet areas).

During the course of a design review process, the stiffness reduction value for all liquefied layers utilised a β value of 0.02. Checks were completed using a higher value of 0.05 to check sensitivity. Where the lower reduction value was utilised, the volumetric strain was not applied.

5.4 Plaxis Results

The result of the Plaxis Assessment confirmed the simplified assessment and had general agreement that a treatment depth of 1.5m to 6.0m bgl would provide a sufficiently thick crust to achieve the performance criteria.

However, locally high point loads from micropile groups required additional treatment to 8.0m below ground level to prevent excessive differential movement.

6 VERIFICATION WORKS

6.1 Resin Injection Overview

Resin Injection is a ground improvement technique designed to be used under existing structures to provide an increase in liquefaction resistance. Densification of the injected soil occurs primarily as a result of an expanding polyurethane resin product. Detailed testing of the technology was carried out in 2013 and 2016 by MBIE and EQC as part of a large-scale liquefaction ground improvement trial. The outcome of the trials has seen the technology included in the MBIE Module 5: Ground Improvement of Soils Prone to Liquefaction. As previously stated, secondary effects such as improvement in composite stiffness cementation, and horizontal stress increases have not been considered.

Injection tubes are driven into the ground through small penetrations (up to 20 mm) at regular intervals, and at each injection point material is injected into the target treatment zone to create the resin-soil matrix. During injection of the treatment zone, the low viscosity resin both permeates the soil to a limited extent, and also penetrates under pressure along planes of weaknesses within the soil profile. The material reacts soon after injection, rapidly expanding to many times its original volume. The expansion of the injected material results in compaction of the adjacent soils, due to new material being introduced into a relatively constant soil volume.

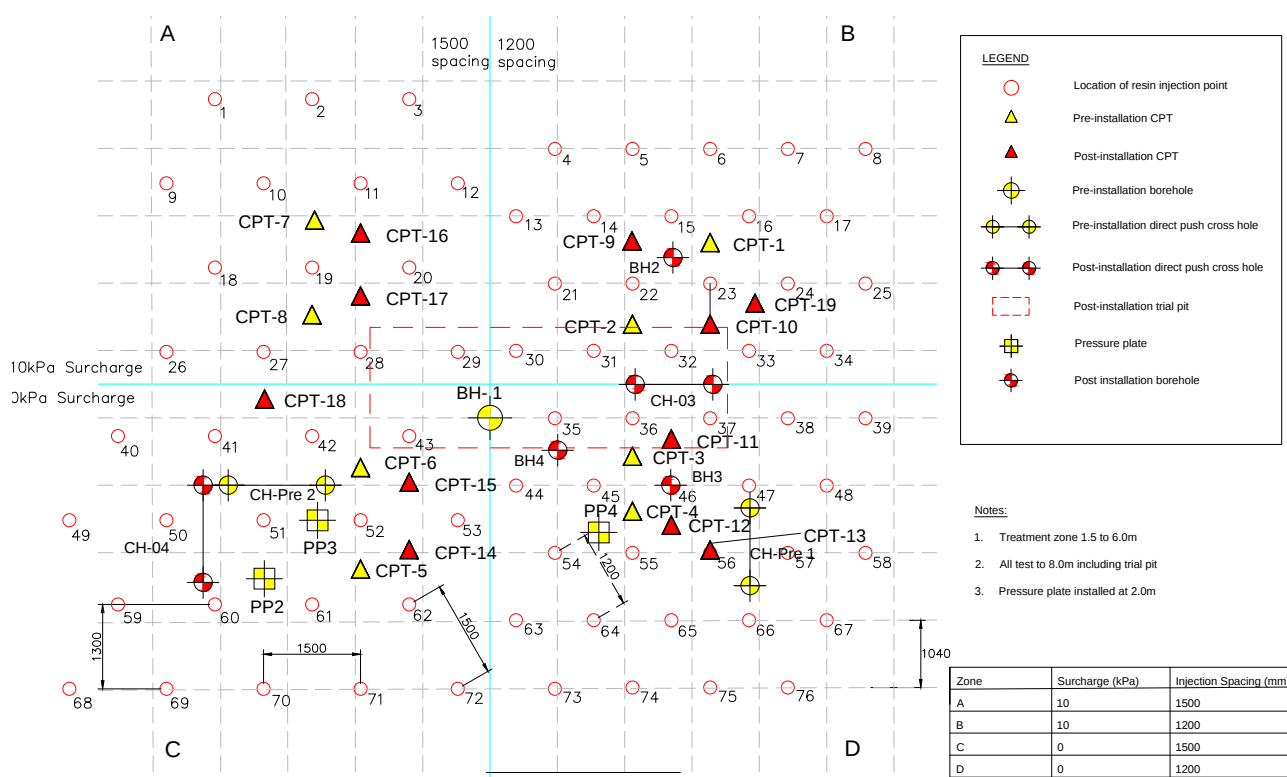


Figure 3: Verification trial injection and testing layout

6.2 Mark-out

An injection array was marked out across the entire treatment area, on a regular grid spacing with reference points. An indicative layout of the Trial area is shown in Figure 3. In-ground service scanning was undertaken to ensure no adverse impact on services from the drilling and injection process. Any injection locations that coincide with adjacent services can be readily relocated.

6.3 Drilling

Penetrations to enable injection works are limited to 20mm in diameter. Standard, hand-held rotary hammer drills are sufficient to enable drilling through floor slabs and footings. Mainmark utilise custom drill lengths of up to 2.5m as standard. Another benefit of this low-impact drilling method is that damage to steel reinforcement is minimised. If required, control strategies can be used to mitigate any concrete dust generation.

6.4 Tube Installation

All injection tubes used for material delivery are 16mm in diameter, and can be installed in continuous or coupled segmented lengths. This enables installation to depths greater than the available head room. Injection tubes are easily installed using hand-held rotary hammer drills. Injection tubes installed below the water table are fitted with sealed driving tips to prevent ingress and blockage prior to injection. Each injection tube is removed upon completion of that location's treatment.

6.5 Injection Process

Injection material is generated within self-contained mobile plant (20ft containerised), which can be located up to 100m from the intended injection locations. Sealed hoses transport the material from the plant to the delivery point.

The level of improvement targeted determines the following key parameters:

1. Injection sequence
2. Injection volumes (e.g. per vertical metre)
3. Target improvement / densification
4. Tube extraction rate (static or continuous)
5. Allowable structure movement

Items 2 – 5 form part of the injection cut-off criteria, in addition to any other requirements.

A capping layer is typically required to provide increased confinement for the ground improvement zone. This is injected first, and is followed by injections into the remaining ground improvement zone, as shown in Figure 5. A tube extractor can be used for continuous material injection.



Figure 4: Capping and target improvement zones (left); and Resin Injection process (right)

6.6 Results

Geophysical testing was carried out before and after ground improvement. This included boreholes, CPT, direct-push crosshole testing (DPCT), and earth pressure cells. The post-improvement testing was carried out 14 days after injection completion to account for pore water pressure dissipation. However, the earth pressure cell data showed that dissipation effects were complete within 7 days post-injection works.

From the CPT analysis, an increase of 30% in q_{c1Ncs} was measured in the top 3m, a 3% increase in the gravel layer from 3 – 5m, and an 18% increase from 5 – 6m. As noted in Traylen et al. (2017), a general trend of decreasing efficiency of improvement can be seen in the soils with a higher starting q_{c1Ncs} values. However, as shown for the SLS2 case in Figure 6, these soils already have a factor of safety greater than 2. As such, the final design will seek to increase efficiency by reassigning the injected material from the 3 – 5m zone to the zones directly above and below.

The DPCT data showed an increase in G_o of 16% in the top 3m, a 7% increase from 3 – 5m, and a 24% increase from 5 – 6m, noting a similar trend as the CPT analysis, however with increased effectiveness in the deeper, more confined sand layer. No significant trends were observed in the degree of saturation (V_p data) pre- and post-injection.

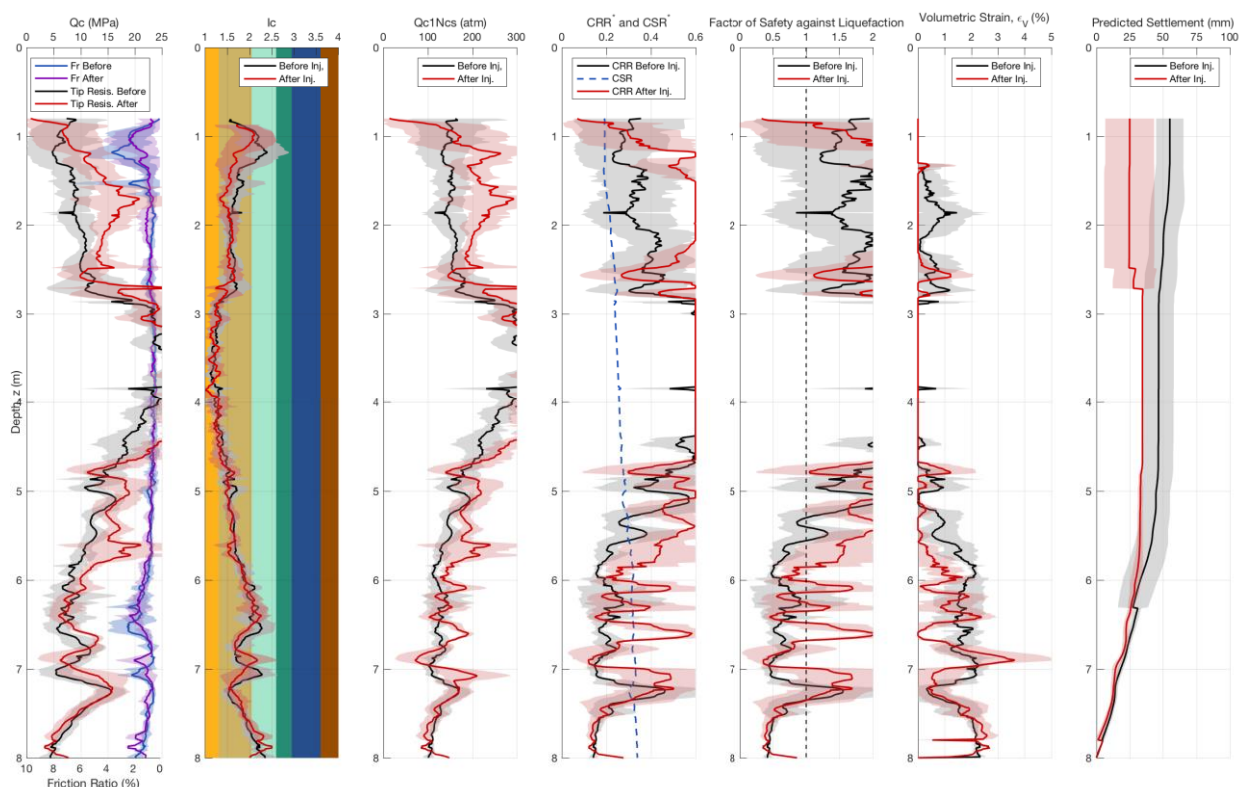


Figure 6: Pre- and post-improvement liquefaction analysis (B&I, 2014) for the SLS2 case

7 LESSONS LEARNT

Coffey's initial involvement with the project dates to 2014, while Mainmark became involved from early 2018. During this time events such as Kaikoura, and lessons learnt from the Christchurch Sequence have greatly changed the way we approach these critical projects. Some of these lessons are listed below:

- More testing up front – 10-20 additional CPT's would have provided a better understanding of site variability.
- Large scale lab testing of the affect resin seams has on the rotation of soil particles.
- Mass permeability of the resin block.
- Site testing to allow benchmarking of Plaxis Results.
- Limitations of Pseudostatic Plaxis Assessment.

8 SUMMARY

Although further research/testing is required to establish a better understanding of the impact the resin is having on the soil behaviour during a seismic event, there is clear indications of an improvement in soil behaviour and a reduction in susceptibility to liquefaction.

The simplified assessments, Plaxis pseudo-static assessment and the data collected from the verification trial shows ground improvement meets the Performance Criteria.

In general, liquefaction occurring below 6m is considered to have a low impact on the existing structures. Although total reconsolidation settlement will continue to increase with increasing acceleration.