Innovative Resin Injection Ground Improvement to Build Up Seismic Resilience of Existing Water Structures

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ABSTRACT

The existing Wellington Water's Waterloo Water Treatment Plant (WTP) in Wellington, New Zealand is an important post-earthquake facility for the Wellington region. The WTP is founded on soils prone to liquefaction and cyclic softening in a large earthquake. Options for seismic strengthening of the ground beneath the WTP are currently being considered. A methodology for improving liquefiable soils beneath the WTP must ensure that the plant is kept operational during the construction of ground improvement. Extensive field and laboratory testing of the site soils, including cyclic triaxial tests has been carried out. Innovative Resin Injection (expanding polyurethane resin) has been identified as the most efficient ground improvement option for the WTP. WSP's geotechnical team, together with Mainmark contractors and Wellington Water, have designed and carried out a complex full-scale Resin Injection trial next to and beneath the WTP structures to refine the resin injection methodology and check the level of soil improvement that can be achieved. The trial required detailed heave monitoring of the plant's floor and walls in addition to recording pipelines deformation in order to avoid causing damage to the plant structures and equipment. The trial indicated that Resin Injection resulted in a significant reduction in the treated soils' liquefaction potential, as well as reduction in the predicted WTP structures' seismic settlement.

1 INTRODUCTION

Eight wells supply water from the Waiwhetu aquifer, beneath Lower Hutt, to the Waterloo Water Treatment Plant (WTP), which was commissioned in 1981. The WTP is located in a developed area bounded by the Waterloo Railway Station, rail tracks, busy roads, and a parking area (Figure 1). Waterloo WTP has a maximum production capacity of around 115 ML/day. Water treated at Waterloo WTP supplies Lower Hutt and, mixed with water from Wainuiomata, also supplies Wellington's business district and southern and eastern suburbs contributing about 40% of the total region's water supply on average.

Figure 1: Waterloo WTP aerial view.

Wellington Water aims to continuously improve the seismic performance of the water supply network. The WTP includes two large water reservoirs with total volume of 1600 m^3 and is an important post-seismic event facility for the Wellington region. It is critical for the plant to be operational after a seismic event to underpin the region's social and economic recovery. The WTP's buildings have been seismically strengthened, and ground improvement options to mitigate liquefaction susceptibility of the ground are currently being considered to improve the seismic resilience of the WTP.

WSP's geotechnical team faced the challenge of developing a methodology for improving liquefiable ground beneath the WTP while keeping the plant operational.

2 SITE CONDITIONS AND PLANT STRUCTURES

The surrounding topography is flat and lies at an elevation of approximately 6.0 m above mean sea level. Extensive geotechnical investigations comprising geophysical tests, boreholes, CPTs and laboratory testing have been carried out. Figure 2 shows geotechnical test locations and names of different WTP structures. WSP geotechnical team has also supported a complex consenting process and used specialised drilling techniques to protect the artesian aquifer located at approximately 20 m depth. A 3D ground model was developed in Leapfrog based on recent and historical CPTs and boreholes. A longitudinal cross-section of the site and ground model is presented on Figure 3.

On the northern side of the plant, the natural ground is composed of approximately 6.0 m of silt and clay, over a silty sand and sandy gravel layer with a variable thickness of 5.5 - 7.0 m, overlying the Waiwhetu gravels. On the southern side of the plant (beneath the reservoirs) the natural ground consists of approximately 7.0 m of sand and gravel mixtures, over a silty sand layer with a thickness of approximately 4.0 m, overlying the Waiwhetu gravels.

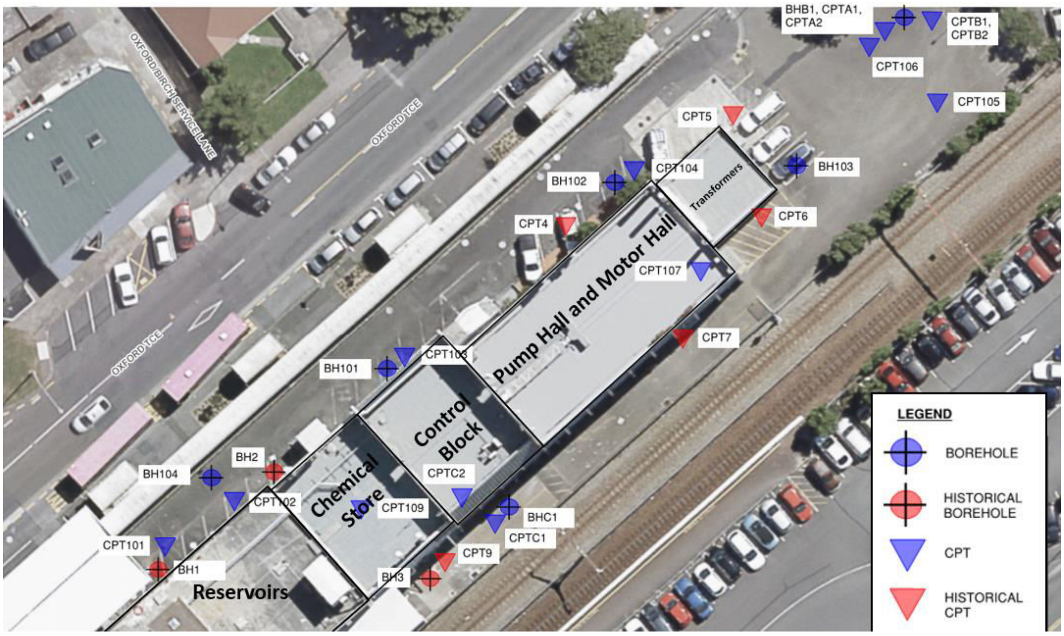

Figure 2: Waterloo WTP geotechnical test location plan.

The structural drawings show that the top 2 - 3 m of in-situ soil had been removed and replaced with well-compacted granular fill within the whole footprint of the plant. All of the WTP structures are founded on shallow (strip, pad and raft) foundations. The control block, chemical store and pump hall are founded at approximately 2.2 m - 2.7 m below the existing ground surface level. The reservoirs, the transformers and part of the motor hall foundations are founded at about 0.6 m below the ground surface level.

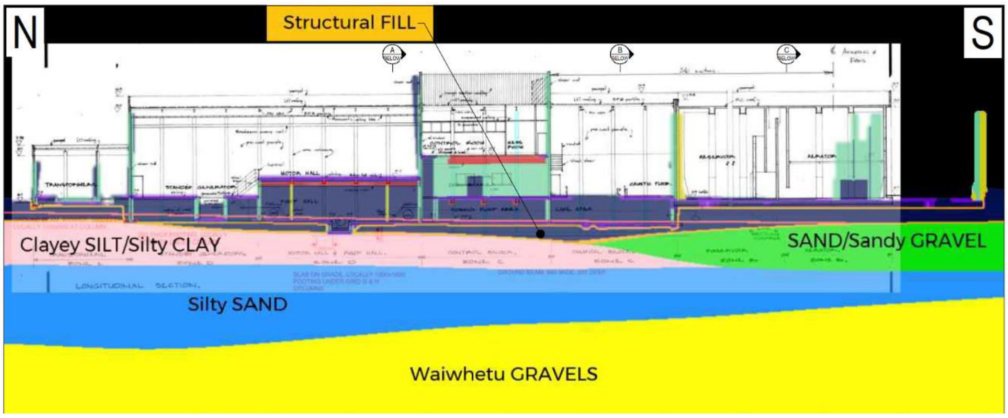

Figure 3: Longitudinal cross-section of the plant from Leapfrog model

3 SEISMIC HAZARD

Seismic design requirements and performance levels were specified by Wellington Water. The structural design basis is summarised in Table 1.

Table 1: Structural design basis.

Structure categorisation and Design basis	
Design working life	100 years
Importance level	Level 4
ULS Return Period	2500 years
SLS2 Return Period	1000 years
SLS1 Return Period	25 years
Site sub-soil category	Class D (Deep or soft soils)

Seismic hazard for geotechnical design was determined based on Waka Kotahi Bridge Manual (NZTA, 2018), NZS1170.5 and site-specific probabilistic seismic hazard analysis (PSHA) as summarised in Table 2.

Table 2: Geotechnical design basis.

	NZTA Bridge Manual	**NZS1170.5**	**Site-specific PSHA**
Peak Ground Acceleration, PGA_{SLS2}	0.45g	0.58g	0.83g
Effective Magnitude, $M_{eff,\ SLS2}$	7.1	7.5	7.7
Peak Ground Acceleration, PGA_{ULS}	0.63g	0.81g	1.17g
Effective Magnitude, $M_{eff,\ ULS}$	7.1	7.5	8.18

The ground motions parameters (PGAs and Magnitudes) are crucial for the design of ground improvement and for the seismic performance of soils and foundations. The degree of improvement that needs to be achieved to increase the soil strength and limit/prevent liquefaction is governed by the ground motion parameters. Also, ground motion parameters will affect liquefaction-induced settlement (if the whole depth of liquefiable material is not improved) and will govern geotechnical design (the injection grid, the amount of resin to be used and the depth of ground improvement). For higher PSHA ground motion demands, the ground would need to be densified to a higher level. In addition, higher level of PSHA seismic shaking may result in larger post-ground improvement settlements and differential settlements, larger lateral forces and base shear forces applied to the soils.

4 SEISMIC DESIGN APPROACH

The Waterloo WTP comprises a water retaining reservoir and treatment and pumping buildings. Wellington Water provided preliminary direction on the design seismic events they would like to adopt.

The SLS2 criterion for the WTP reservoirs is that they must maintain operational continuity. This is generally interpreted as a minimal loss of water (due to cracking or movement) and the ability to supply water with minimal or no repairs being required immediately after the earthquake. Only life safety requirements had to be considered for the ULS event. Wellington Water's preference was to use PSHA PGA and Magnitude for SLS2 event and NZS1170.5 PGA and Magnitude for the ULS event.

A geotechnical investigation programme was developed, and a ground improvement trial was designed and carried out to confirm site soil properties and potential for liquefaction. The objectives of the trial were also to understand whether various soil layers are able to be improved by resin injection sufficiently to mitigate the liquefaction risk, to estimate the cost of achieving the selected level of improvement, and to confirm that the level of improvement is sufficient to meet the specified seismic performance requirements.

5 LIQUEFACTION AND CYCLIC SOFTENING

Representative CPTs of each plant building structure (building unit) were analysed in terms of extent of liquefaction and free-field settlement for different earthquake scenarios. Our analysis indicated that the Silty Sand (at approximately 6.0 m - 12.0 m below ground level across the site) is prone to liquefaction, with the liquefaction-triggering PGAs between 0.14g and 0.16g for a M_w 7.5 earthquake. When fully liquefied, the silty sand layer can experience a total free-field settlement of up to 100 mm. In addition to this, our assessment indicated that the sandy gravel (at approximately 2.0 m - 7.0 m depth below ground level) located towards the southern end of the plant is also prone to liquefaction, with a liquefaction-triggering PGA between 0.15g and 0.19g for a M_w 7.5 earthquake. When fully liquefied, the sandy gravel can experience a total free-field settlement of up to 140 mm.

Liquefaction potential of the silts and clays at the WTP south end could not be reliably assessed using simplified methods, and therefore cyclic triaxial tests were carried out in the University of Auckland testing laboratory. Four tests were carried out at different cyclic stress ratios to confirm whether the material is prone to liquefaction (characteristic of loose sandy soils) and/or cyclic softening (loss of cyclic strength of clay-like soils) for different ground shaking levels. Typical test data corresponding to the SLS2 event seismic shaking level is shown in Figure 4.

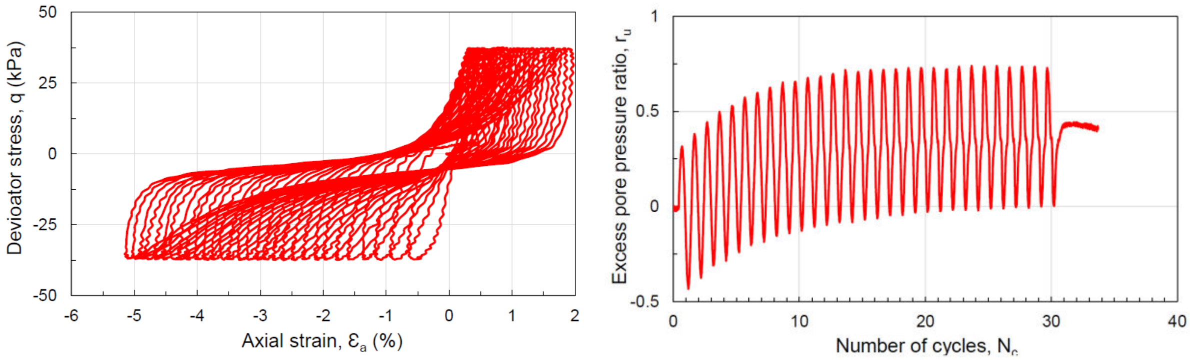

Figure 4: Deviator stress against axial strain (left); Excess porewater pressure ratio against number of cycles (right).

The cyclic triaxial test results show a marked reduction in the stiffness of the soil as loading progresses. However, excess porewater pressure reaches a maximum of 75% initial effective confining pressure. This means the soil has not ‘liquefied’ in the classical sense, instead, the soil has undergone cyclic softening.

6 RESIN INJECTION GROUND IMPROVEMENT

Resin injection ground improvement is a technique designed to improve soils under existing structures and mitigate their liquefaction potential. Densification of the site soils occurs primarily as a result of an expanding polyurethane resin product injected into the ground. Detailed testing of resin injection was carried out by MBIE and EQC in 2013 as part of a large-scale liquefaction ground improvement trial. Resin injection ground improvement technique has been included in the MBIE/NZGS Module 5: Ground Improvement of Soils Prone to Liquefaction.

For this project, injection tubes were driven into the ground through small penetrations (approximately 20 mm diameter) at regular intervals, and at each injection point resin was injected into the target improvement zone to create the resin-soil matrix (Figure 5). During injection of the treatment zone, the low viscosity resin both permeates the soil to a limited extent and 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.

In predominantly granular soils, the resin spreads relatively uniformly along the injection depth, expanding primarily in the horizontal direction and, consequently, generating minimal ground heave. In predominantly fine-grained soils, however, resin spreads horizontally, by forming horizontal resin veins which result in higher ground heave when expanding for the same quantity of injected material.

Figure 5: Resin Injection process (left) and hand-exhumed resin veins (right)

7 GROUND IMPROVEMENT TRIALS

Ground improvement trials were carried out at two trial pads, one on the northern side of the site (North Trial Pad) in a carpark area and the other on the southern side of the site (South Trial Pad) under the existing plant structure. The size of each trial pad was approximately 10.0 m x 6.0 m. A concrete slab was built on the North Trial Pad to work as a surcharge on the trial area to model the load applied by the buildings and to reduce heave. The locations of the trial pads were chosen to minimise disruption to Wellington Water operations and were aimed at injecting resin into the different materials across the plant to better understand the level of improvement that can be achieved for the different soil types. A 3D BIM illustration of the injection trial beneath the WTP and a site photo are included in Figure 6. The trial required detailed monitoring of the plant floor and walls' heave and existing pipelines' deformation to avoid damage to the plant structures and equipment, and to ensure that the plant remains operational.

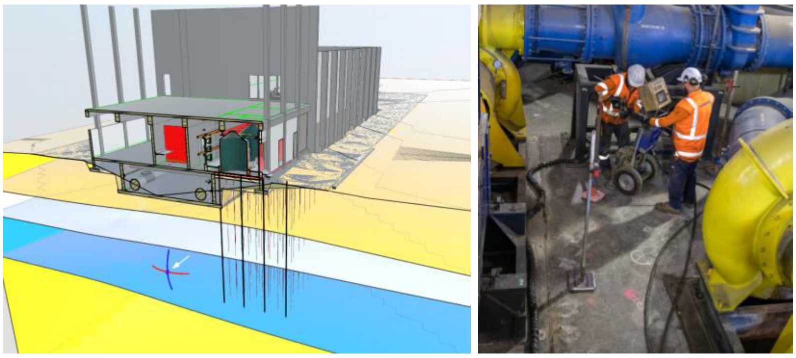

Figure 6: 3D BIM model of the injection trial beneath the WTP (left); Resin injection injection in progress (right)

8 EFFICIENCY OF RESIN INJECTION

Pre- and post-resin injection testing indicated that substantial level of soil densification was achieved which reduced the site soils' potential for liquefaction and associated loss of strength and stiffness, and substantially reduced seismic settlement of foundations.

Figure 7 below illustrates the level of improvement achieved at the North Trial Pad by comparing pre and post-injection CPT-based factors of safety against liquefaction and total vertical settlement.

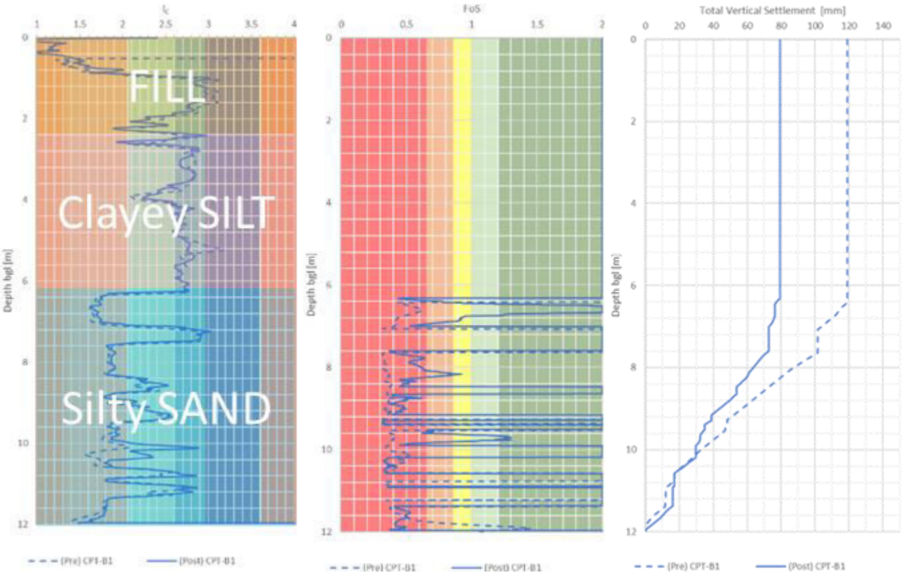

Figure 7: Comparison of pre and post- injection CPT-based liquefaction assessment results: soil behaviour type index (left), factor of safety against liquefaction (middle), total vertical settlement (right).

Most of the improvement was achieved in the silty sand layer. The clayey silt layer was also improved but the trial provided evidence that resin injection in this layer generates significant amount of heave.

The results of the resin injection trial enabled estimating the level of improvement that could be achieved across the Waterloo WTP footprint. A comparison of the estimated pre-treatment and the post-treatment liquefaction-induced free-field settlements is presented in Figure 8.

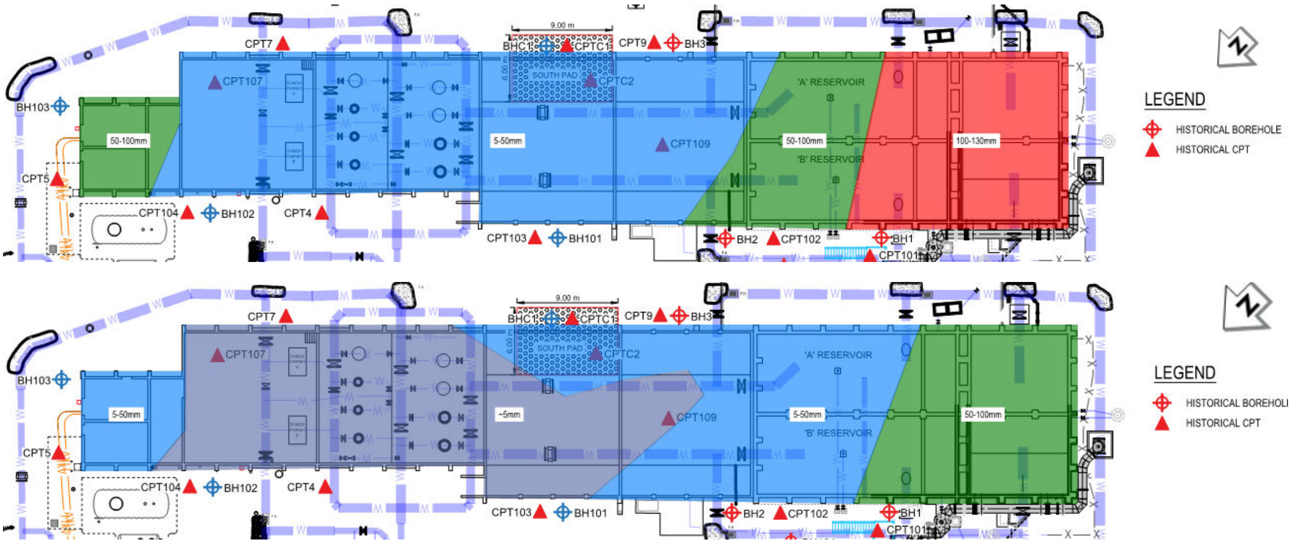

Figure 8: Comparison of pre-treatment (top) and post-treatment total free-field settlements.

Comparison of pre- and post-injection total and differential settlement for the different WTP structures based on the analysis incorporating the results of the trials is shown in Figure 9.

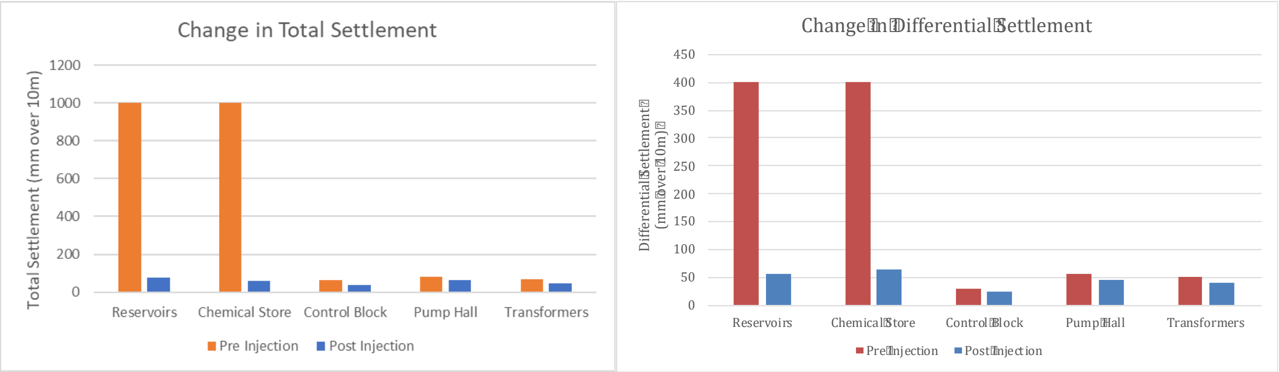

Figure 9: Comparison of pre- and post-injection total (left) and differential settlement (right) for the different WTP structures.

Both the free-field and the ratcheting settlements were included in the assessment of pre- and post-injection total settlement of the structures. Resin injection ground improvement not only reduced the risk of liquefaction, but it also improved soils' strengths and bearing capacities.

Our analysis indicated that resin injection would substantially improve the seismic performance of the reservoirs and the chemical store structures. There would be low return on investment to apply resin injection for the control block, pump hall and motor hall. However, even for these structures, the total and differential settlements would still be reduced by approximately by 50% and 30% respectively. The analysis (Figure 9) also demonstrates that resin injection would result in a more uniform settlement performance of the structure.

9 CONCLUSIONS

The cyclic triaxial tests indicated that some of the site soils are not prone to liquefaction in the classical sense but can instead undergo cyclic softening. Resin Injection is one of very few methods available to improve the ground under existing structures. The full-scale field trials indicated that Resin Injection resulted in a significant reduction in the treated soils' liquefaction potential, as well as a reduction in the predicted WTP structures' seismic settlement and avoidance of seismic bearing capacity failures. The efficiency of ground improvement is highly dependent on the nature of the site soils. Good levels of improvement were achieved in granular materials and silts, while clays indicated a low level of improvement and generated large heave due to inability to consolidate quickly.

10 ACKNOWLEDGEMENTS

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