Resin injection as a ground improvement method

N Traylen
Geotech Consulting Ltd, Christchurch, NZ
ntraylen@geotech.co.nz (Corresponding author)

T Hnat
Mainmark Ground Engineering Ltd, Christchurch, NZ
thnat@mainmark.com

R Wentz
Wentz-Pacific Ltd, Napier, NZ
rwentz@wp-geo.co.nz

L Wotherspoon
University of Auckland, Auckland, NZ
l.wotherspoon@auckland.ac.nz

S van Ballegooy
Tonkin + Taylor, Auckland, NZ
SVanBallegooy@tonkintaylor.co.nz

R Deller
Mainmark Ground Engineering Ltd, Christchurch, NZ
rdeller@mainmark.com

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ABSTRACT

There are few practical methods currently available for liquefaction mitigation beneath existing structures, despite a growing demand for this due to a significant number of structures being targeted for seismic upgrading. One such method that is viable for liquefaction mitigation beneath existing structures is the injection of expanding resin. This method densifies soils (of suitable composition) and thus increases liquefaction resistance (i.e. increases the relative density and therefore the cyclic resistance ratio of the soils), as well as improves the composite stiffness of the ground.

This paper describes the results of a controlled study that has been carried out into the efficacy of this ground improvement technique. In the study, three test sites in the Christchurch 'Red Zone' were selected for the construction of resin-injected test panels. The soils were assessed using Cone Penetrometer Test (CPT), cross-hole geophysical testing, and dilatometer testing (DMT), to examine the effects the injected materials have had on the density and stiffness of the soils, and therefore their likely liquefaction performance.

The results of the study show that significant improvements in soil density, stiffness and strength were achieved, demonstrating that resin injection is a viable ground improvement method.

1 INTRODUCTION

Injection into the ground of expanding resin mixtures (at relatively shallow depths) has long been used for the level correction of buildings. The injection and expansion process also compacts or densifies the ground, and therefore this process has potential uses in liquefaction mitigation projects, or other applications where ground densification is required.

The aim of this study was to examine on a formal basis whether resin injection is a viable form of ground improvement, primarily for liquefaction mitigation. This has been achieved through a series of trial injection panels, where pre-injection and post-injection soil density and stiffness have been compared by cone penetration testing (CPT), geophysical testing (Vs and Vp testing), dilatometer testing (DMT) and plate load testing (PLT).

2 SOIL IMPROVEMENT MECHANISM

With this technology liquefaction mitigation primarily occurs from densification of the soil by an aggressively expanding polyurethane resin product (although other secondary effects such as improvement in composite stiffness, cementation, etc are also present). With this method, injection tubes are driven into the ground at regular intervals, and at each injection point an injection nozzle is attached to the injection tube. Multipart materials are mixed at specific pressures and temperatures at the nozzle; the live composite material ('resin') is then pumped to the base of the tube, where it enters the soil matrix. Either 'top down' or 'bottom up' methods can be employed. In a typical 'bottom up' installation the tube is withdrawn either in set stages with set volumes of material injected at each stage, or it is withdrawn slowly on a continuous basis with set volumes of material being injected per unit length that the tube is withdrawn.

The low viscosity resin is injected at controlled pressures and penetrates the soil mass along pre-existing planes of weakness or through fracturing of the soil mass. The resin also permeates the soil mass to a limited extent depending on the porosity of the soil. The resin mix chemically reacts soon after injection (at controllable 'rise' times). The material expands rapidly to many times its original volume and changes from a fluid form to an (inert) solid one. Depending on soil density, confinement pressure, and the resin material selected, the expansion volume can be in the order of 5 – 15 times the injected volume (or more if required). The looser the soil, the greater the expansion for a given resin mix. 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. The resin injection process has been observed to result in a 'veining' of material distributed through the soil mass as dykes, sills or networks of sheets or plates, typically tens of millimetres thick (refer to Figure 1).

Figure 1. Hand-exhumed resin veins (left) and hydro-exhumed resin veins (right).

3 BACKGROUND AND RECENT USE

Ground strengthening by polymer injection has been previously used in Turkey (Erdemgil et al. 2007). Liquefaction mitigation by Resin Injection in New Zealand has been examined in some detail on two recent occasions. A preliminary trial was carried out as part of the 2013 EQC Ground Improvement Trials, and resin injection was also used on a 5400m2 commercial building rehabilitation project in 2015/2016.

3.1 EQC ground improvement trials, 2013

In 2013 a series of ground improvement trials were undertaken in Christchurch by EQC (in press) to examine the performance of various forms of ground improvement, including a preliminary examination of resin injection. The resin injection panel that was tested showed an increase in liquefaction resistance by a number of mechanisms: (i) the overall density of the soil increased, as measured by CPT tip resistance, (ii) shear wave velocity testing showed that the composite stiffness of the improved soil block increased, (iii) the cyclic strains in the soils during shaking were decreased, as measure during vibroseis T-Rex testing, and (iv) pore pressure response during shaking was significantly decreased. The result of these effects was that the ground surface settlements during subsequent blasting trials were also much reduced.

3.2 Commercial shopping centre

Three adjoining large format retail buildings that had suffered liquefaction-related settlement damage in the Canterbury Earthquake Sequence (up to 160mm differential settlement across the 5400m2 combined building footprint) were relevelled, repaired, and upgraded in 2015/2106. The first stage of the remediation works consisted of liquefaction mitigation by densification and stiffening of the underlying shallower soils by Mainmark Ground Engineering Ltd, using their TeretekTM resin injection methodology.

The resin injections resulted in increases in qc1ncs (i.e. the clean sand equivalent of the corrected CPT tip resistance) in the order of 40%, and decreases in calculated settlements in the treated zones of 40-80% at 100-year return periods of shaking (Traylen et al. 2016, Hnat et al. 2017).The project therefore demonstrated that resin injection is a viable technology for ground improvement, and is particularly useful for liquefaction mitigation or ground densification beneath existing structures. Furthermore, the low level of intrusion required to carry out the process was a particular advantage for this operation, as the three retail outlets (including a large supermarket) were able to continue trading uninterrupted through the busy Christmas trading period.

4 RED ZONE SITE SELECTION AND CHARACTERISATION

The 2013 EQC ground improvement trials were carried out in Christchurch in the abandoned 'Red Zone' of Avondale and Bexley. This land is some of the worst affected from the Canterbury earthquakes (due to liquefaction damage). The sites used in this study (Table 1) were adjacent to the areas used in the EQC trial process - they were selected to avoid areas which had been affected by the installation of other ground improvement methods and instruments, and also to avoid areas affected by liquefaction-inducing blasting trials that were carried out in the 2013 study.

Table 1. Trial Sites

Site	Soils	CPT q_c	Water Table	
			Measured*	GNS**
3 – Breezes Rd, Avondale	Silty sands and some silts overlying clean sands at 4.5m depth.	2-5 MPa in the upper 3m; 11 MPa to 5m depth; 5 to 11 MPa to 8m depth.	1.1 – 1.2m	1.1m
4 – Ardrossan St, Avondale	Silty sands and sandy silts overlying clean sands at 2.5m depth.	2-3 MPa in the upper 3-4m; 10 - 12 MPa down to 7m; 5 to 10 MPa to 8m depth.	1.1 – 1.25m	1.1m
6 – Onepu St, Bexley	A predominantly sandy site	Increasing from 2-4 MPa at 1m depth to 10-12 MPa at 4m depth; 7-11 Mpa to 5m depth; 10 -14 MPa to 8m depth.	0.65 – 0.85m	0.8m

* measured Sept – Nov 2016 ** van Ballegooy et al (2014)

5 TEST PANEL LAYOUTS AND TESTING REGIME

Each of the 8m x 8m test panels was set out with a 1.2m triangular grid of resin injection points (Figure 2). The tests were CPT, direct-push crosshole (Vs/Vp), dilatometer ('DMT') and plate load tests ('PLT'). Borehole drilling and laboratory testing was also carried out to determine soils fines contents.

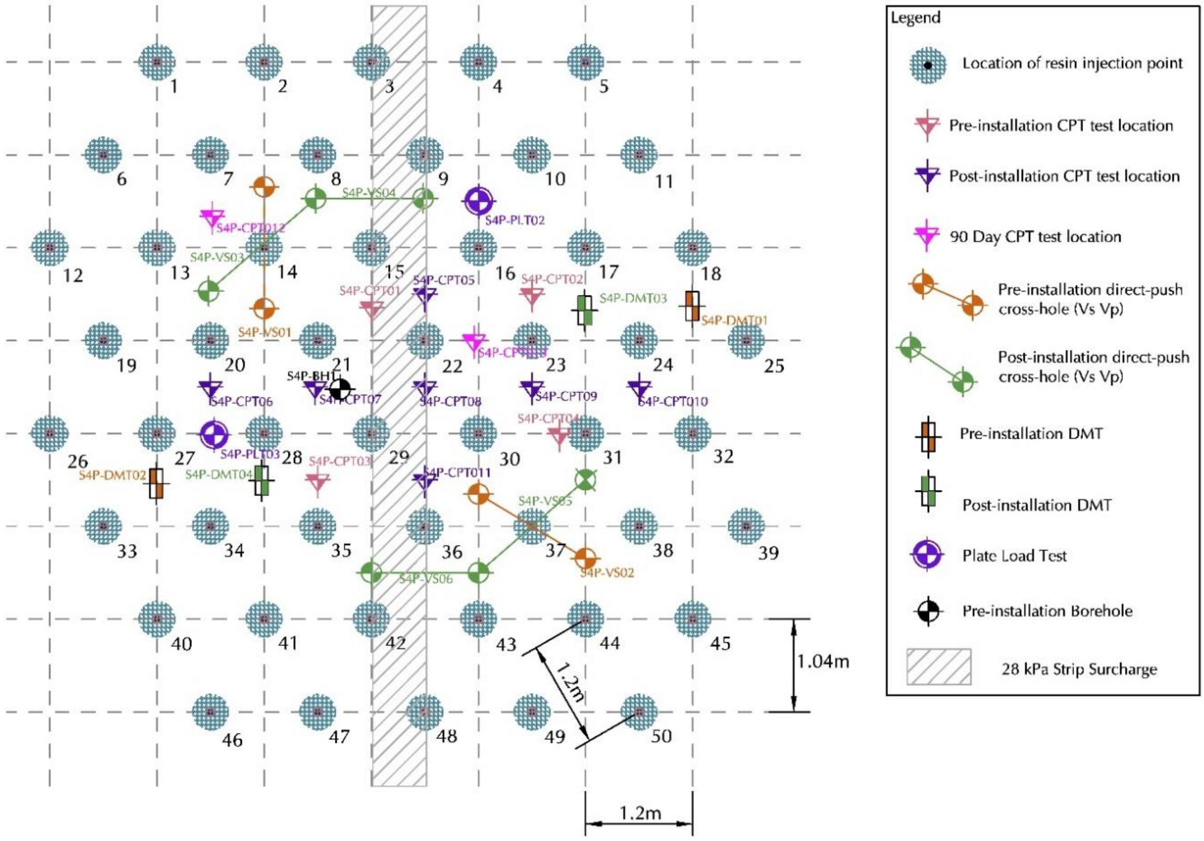

Figure 2 Site 4 installation and testing layout

Table 2. Pre- and post-injection testing

Test	Number carried out at each panel	
	Pre-injection	Post-Injection
CPT	4	7
Direct-push Crosshole (Vs/Vp)	2	4
Dilatometer tests	2	2
Plate load tests	2	2
Borehole	1	-
Fines Content Lab test	3-4	-
Plasticity Index Lab test	0-2	-

Plywood was laid on the ground (over compacted gravel) and then concrete blocks were laid to give a 14 kPa surface load. Steel plate was placed over the blocks to provide a stable working platform. Additional blocks were then laid to superimpose a 28 kPa strip footing load. Pilot holes were drilled and cored through the steel plate, concrete blocks, and plywood to allow the installation of the grout tubes into the ground. The surcharge loads were selected to model both a 2-level unreinforced masonry building ('URM'), as well as a large format commercial building. In each case an assumed 10 kPa floor load was used. Analysis demonstrated that the concrete blocks, along with an additional 28 kPa 'footing' strip load created foundation / floor surcharge stresses generally in the mid-range of those for the modelled buildings.

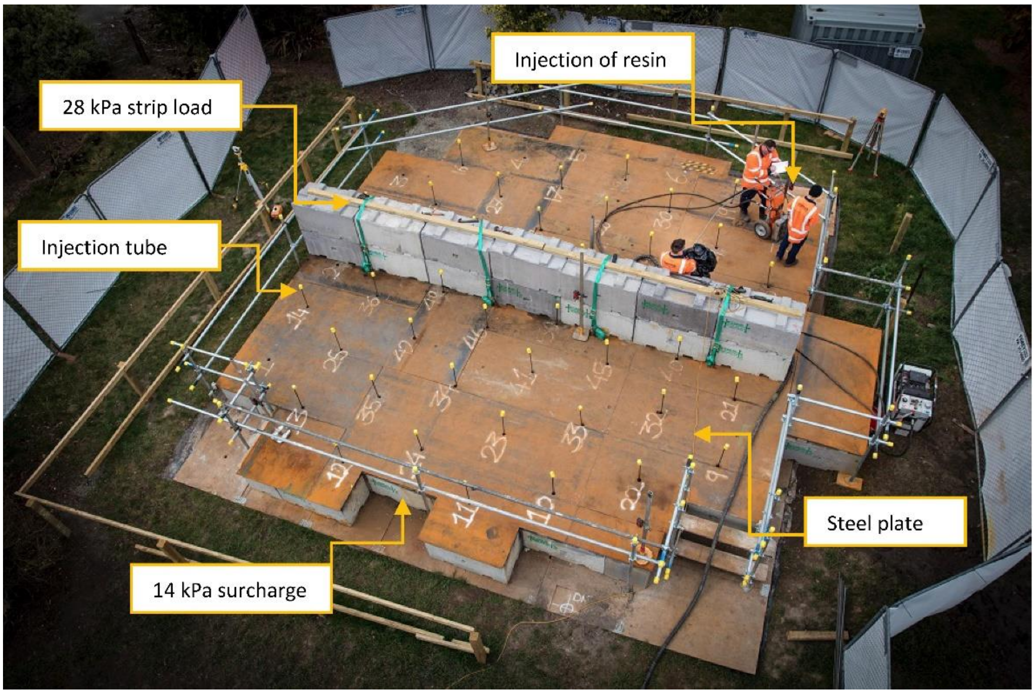

Figure 3 Site 3 aerial view of trial panel resin injection

The ground was treated with injected resin by first applying a ‘capping layer’ at 0.5 – 1.5m, and then injecting from 6m depth upwards on a ’bottom up’ basis. After a period of at least two weeks the concrete blocks were removed, and post injection testing was carried out. One of the panels was partially exhumed to expose the resin veins in the ground (see Figure 1 in Section 2).

Ground heave was observed, averaging 40 to 70mm (σ = 30mm) across the three sites – however there was no attempt made to control ground heave in this case, as there were no adverse consequences from this (70% of the lift was created during the injection of the capping layer in the upper 1 to 1.5m of the ground profile). Ground heave and general surface disturbance using resin injection was observed to be noticeably less than that for other technologies such as stone columns or driven piles. Some controlled ground heave can be beneficial in cases where a building also requires level correction. In other cases, allowances need to be made so that the building can accommodate some changes in final floor level. For heavy buildings, or on sites where the soils are only being treated below 2m depth, significant ground heave may not occur at all.

6 RESULTS

There is a clear trend of increased soil densities and stiffness at all sites, with the level of increase varying with soil characteristics. Improvements in the soils are noticeable up to a metre below the base of treatment. Table 3 provides a summary of results across all three sites.

Table 3 Averaged increases in parameters within the treatment zones

Site	q_c	q_{c1Ncs}	D_R	Vs	K_D	k*
3	88%	68%	32%	35%	47%	57%
4	81%	64%	34%	43%	74%	90%
6	101%	76%	27%	51%	150%	52%

*Modulus of Subgrade Reaction

CPT qc increased on average 80 - 100%, or about 4 - 12 MPa. This corresponds to increases in relative density (Dr) in the order of 30%. Modulus of Subgrade Reaction (k) increased 50 to 90% (from plate load tests). Shear wave velocities (Vs) increased on average 40% - 50 to 75 m/s at Sites 3 and 4, and 75 to 100 m/s at Site 6 (demonstrating an approximate doubling of soil shear stiffness). Dilatometer testing showed an increase in horizontal stress index KD of 50-150%. Given the observed increases in CPT qc, static bearing capacities for shallow foundations also increased, and potential for static settlements decreased. (Schmertmann, 1970, 1978).

The averaged results from all site investigation methods at Site 3 are presented in Figure 4. (Similar trends were evident at Site 4 and better results at Site 6, but these have been omitted here due to space constraints for this paper).

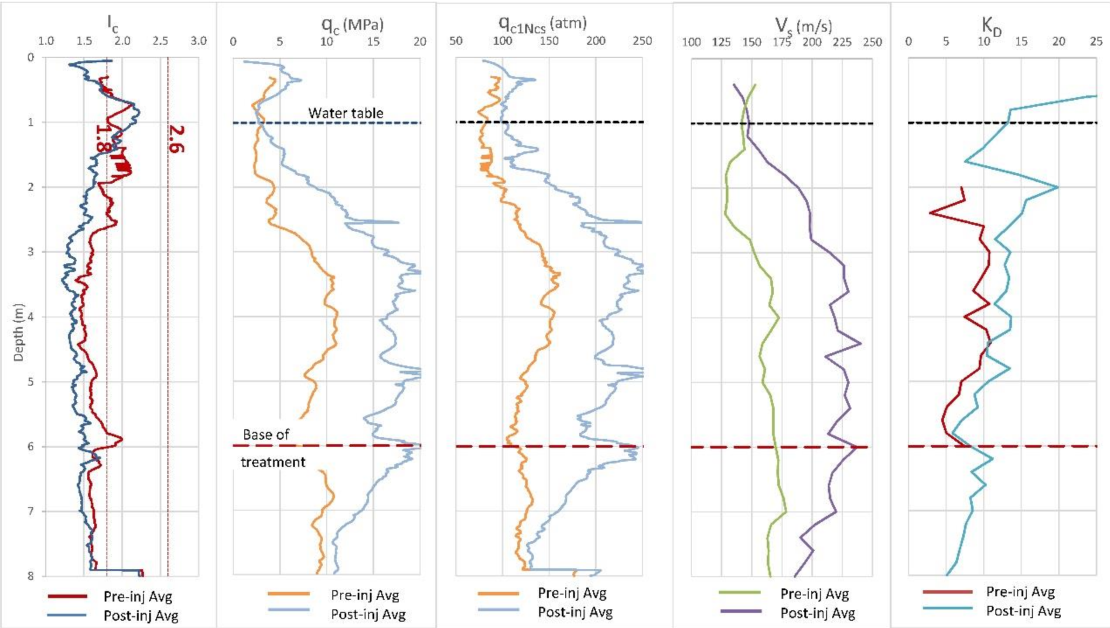

Figure 4 Average test results at Site 3

Figure 5 below provides a summary of qc1Ncs at each site pre- and post-improvement. There is variability in the change in these values at each site through the different soil types; on average, there is a 65 - 75% increase - approximately 50 atm at Sites 3 and 4, and 100 atm at Site 6.

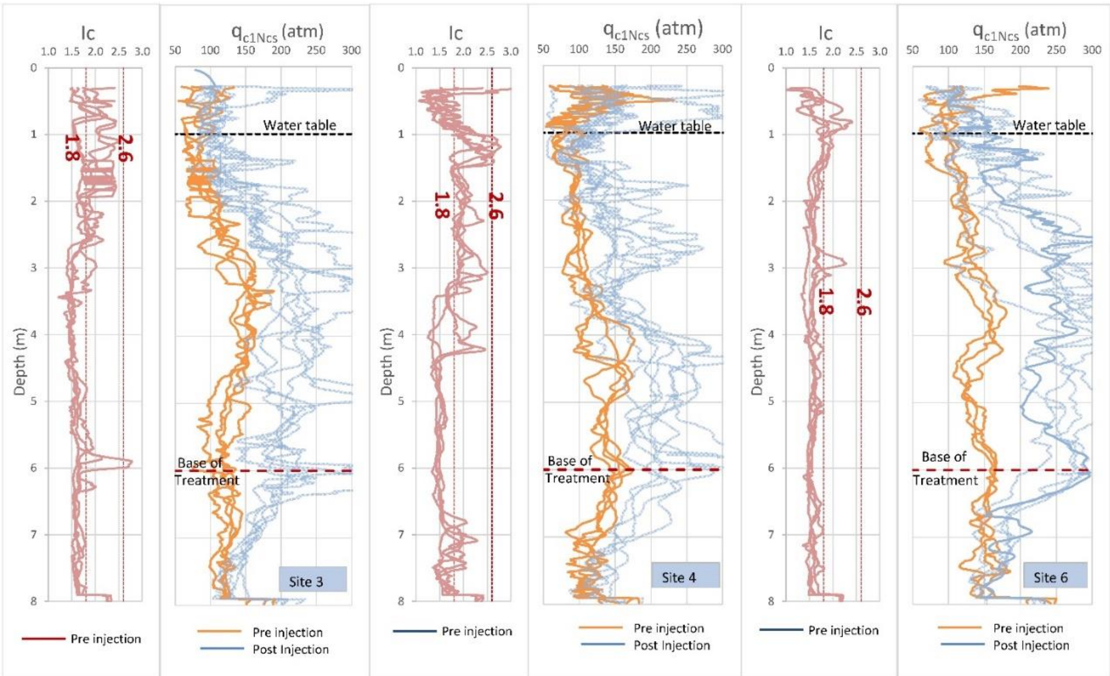

Figure 5 Pre- and post-injection q_{c1Ncs} data

6.1 Calculated liquefaction settlements & liquefaction severity number (LSN)

The CPT data was analysed for liquefaction triggering potential, (Boulanger & Idriss, 2014), and free-field settlements (Zhang et al. 2002). The results for Site 3 are presented in Figures 6 and 7 below, with a selection of return period events for Christchurch highlighted. Considerable reductions in settlements and liquefaction severity number, LSN (van Ballegooy et al., 2014b) are indicated. At the 25-year return period there is a reduction in these values of 90%; as the return period goes out to 500 years this reduction is still over 70%. Across all three sites, calculated liquefaction settlements and LSN values have reduced by 50 – 80%. The implied surface damage potential for these sites from liquefaction is therefore significantly reduced.

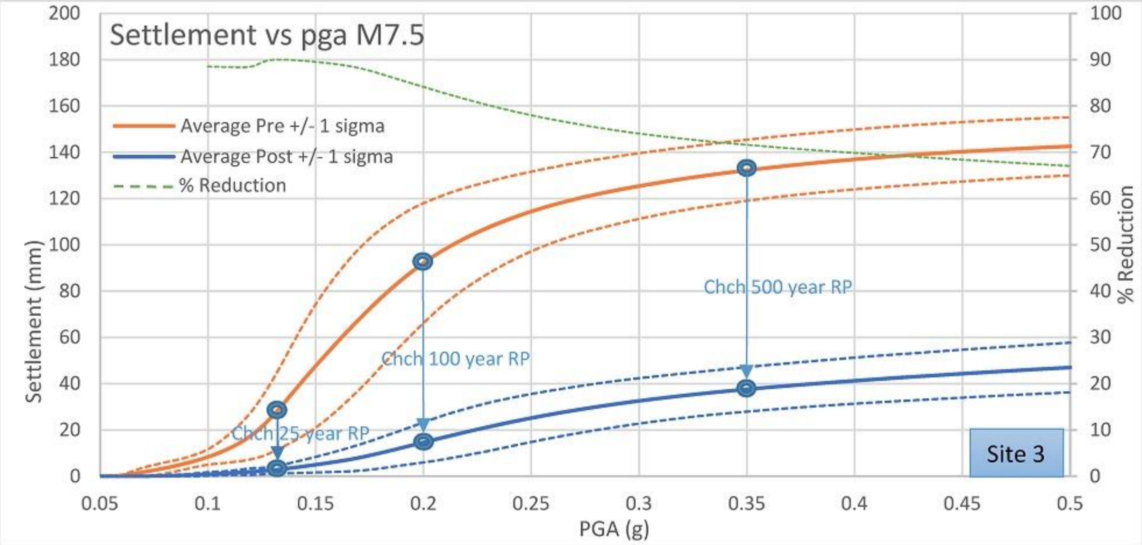

Figure 6 Free-field settlements pre- and post-improvement (Site 3)

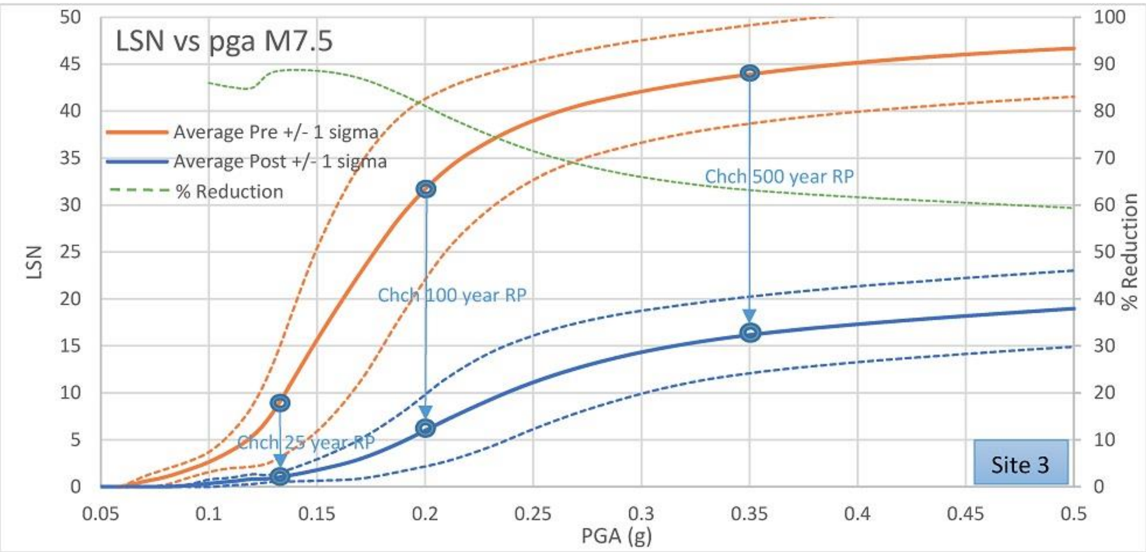

Figure 7 Calculated LSN pre- and post-improvement (Site 3)

7 CONCLUSIONS

The results of the study demonstrate that resin injection can be an effective ground improvement method for mitigation of liquefaction potential, and also for increasing foundation bearing capacities in sandy soils (including the siltier sands – e.g., sandy soils with CPT IC values up to about 2.0). Significant improvements in soil density and stiffness have been demonstrated. It has been noted that decreasing fines content, and increasing confining pressures, lead to better densification effects in treated soils. While the fines content of a soil deposit may constrain the applicability of this technology at any particular site, confining pressures can often be applied through the use of portable kentledge if necessary.

This trial, and commercial application of the technology have shown that the resin injection ground improvement methodology can be successfully applied for liquefaction mitigation or bearing capacity enhancement to cleared sites as well as to ground beneath existing buildings, structures, and infrastructure assets (for which there are currently few viable options).

A more comprehensive research report on these trials (Traylen, 2017) is available on the NZGS website.

8 ACKNOWLEDGEMENTS

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