# Low mobility grout (LMG) at the Southern Cross Hospital to re-level ground bearing floor slabs and improve seismic performance

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## ABSTRACT

Following the seismic events of September 2010 and February 2011, the Southern Cross Hospital on Bealey Avenue, Christchurch experienced liquefaction in the car park and displacement of the ground bearing floor slabs. The piled super structure was in place and the hospital functional albeit with differential displacements of up to 150mm in the floor slabs. Options to re-level the slabs and improve seismic performance were limited by the fact that the work had to be carried out inside the existing building with access and headroom restriction together with live M&E plant. The fact that the hospital remained operational meant that the majority of work had to be done during the 2011Christmas shutdown period. The use of hand tools and low mobility grouting was selected as the only real option to meet these constraints. The paper will describe:

- The low mobility grout (LMG) process
- The design approach and peer review process
- The site trials performed and results
- Operational achievements
- Construction review and design verification

The re-levelling of the slabs was achieved in highly constrained conditions and improvement in the seismic performance was verified from site records and post CPT testing. The project highlighted in particular the response of different soils types to the injection of LMG.

## 1 INTRODUCTION

During the seismic events of September 2010 and February 2011 the REHS strong-motion monitoring station recorded horizontal PGA values of 0.26g and 0.72g respectively. This is located 330m from the Southern Cross Hospital at the intersection of Bealey Avenue and Durham Street. The piled main hospital structure remained operational following both events, however, significant displacement of the ground bearing floor slabs was observed. The Tonkin & Taylor geotechnical assessment revealed the following prevailing ground conditions:

| | |
|---|---|
| 0.0 – 2.5m | Loose to medium dense sand |
| 2.5 – 4.0m | Soft to firm organic silt |
| 4.0 – 8.5m | Interbedded medium dense sand and silt |
| 8.5m - | Dense sandy gravels |

With a groundwater level taken at a depth of 1.0m the potential for liquefaction during a seismic event to depths of 8.5m required evaluation. The report considered grout / resin injection to directly lift the slab, low mobility grout (LMG) to 8.5m depth or replacement of the slabs. Given the operational constraints the replacement of the slabs was considered too disruptive and, unless piled, would not result in any improved seismic performance. Grout / resin injection to directly lift the slabs was a practical solution but was rejected in favour of LMG by the Client advisors because it would result in improved performance during future events. This paper focuses on the LMG process, design, application and verification of the process carried out by RElevel, a joint venture between Brian Perry Civil and Keller Ground Engineering.

## 2 LOW MOBILITY GROUT METHODOLOGY

The LMG process has its origins with Denver Grouting, now part of Hayward Baker Inc. and the Keller group who has used the method extensively in the USA and Japan, with partners Sanshin, to re-level commercial, residential and industrial structures. The method comprises the injection of a low slump cement based grout in to the ground to form durable "bulbs" as shown in Figure 1.

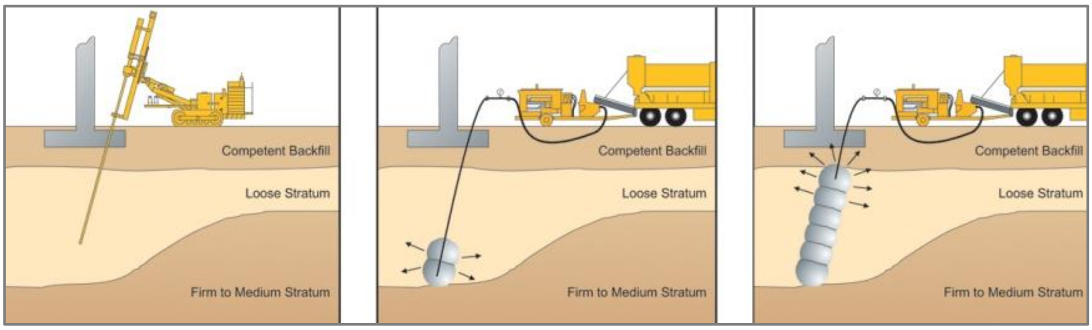


**Figure 1: LMG Methodology**

The grout is injected into the ground at high pressure below the existing foundation which results in displacement of the surrounding soil causing heave of the ground and, dependent upon the soil type, densification of the soil. Typically the grout has the following properties:
The following are highlighted:

- Target slump of the grout = 25 - 50mm
- Compressive strength of grout at 28 days = 2 - 4MPa
- Stable to pump at pressures of 500 to 4000KPa

The grouting sequence can be either bottom up as shown in Figure 1 or can include some top down injection where the foundation is on weak ground or to enhance confinement. Given the depth and soil types present at the site hand-held pneumatic drivers can be used to install the segmental casing to the required depth which minimises access requirements.

## 3 DESIGN OF THE LMG SOLUTION

Whilst the use of LMG had been used in seismically active areas around the world it was relatively new to New Zealand. The technical solution was developed in conjunction with experienced Hayward Baker Inc. engineers and it was considered appropriate to extend the design review process to include University of Auckland and Beca.

Given that the structure had already been subjected to estimated loads greater than the design ULS load case and the LMG was targeted at the ground bearing slabs the design was focussed on the SLS load case. This load case was specified as a magnitude 7.5 event with R = 0.33 and pga = 0.11g with a settlement limit of 25mm. The evaluation of the LMG treatment was based upon the CPT data outside the building foot print. Available software packages LiquefyPro and CLiq were used to evaluate liquefaction potential and estimate the resultant settlements. Cavity expansion theory was used to estimate grout injection volumes to achieve the necessary improvement and thus limit liquefaction potential. From this analysis a target injection volume of 15% in the liquefiable deposits was adopted to define a 2.5m square primary grid spacing with offset secondary grid at the same spacing.

## 4 LMG TRIALS AND RESULTS

The design of LMG for ground improvement and response of the ground to the high pressure injection is challenging to define and further complicated by the variable and interbedded nature of the soils. The rate of pore pressure dissipation is a primary factor influencing the degree of improvement that can be achieved and the heave that may result. To improve understanding of the ground response to LMG injection and essentially verify the design trials were performed in the car park outside the building. The trial areas comprised 6 primary and 2 secondary injection points with volume and injection pressure monitoring. CPT testing was carried out between the grouting points and adjacent to the test area as a reference.

During the Trial 1 the target 15% injection volume was achieved in the liquefiable zones at 1.0 to 3.0m depth and 5.0 to 8.0m depth, however, the surface heave was greater than 100mm. The aim of the Trial 2 was to limit the surface heave to 25mm; the actual volume injected was 11%.

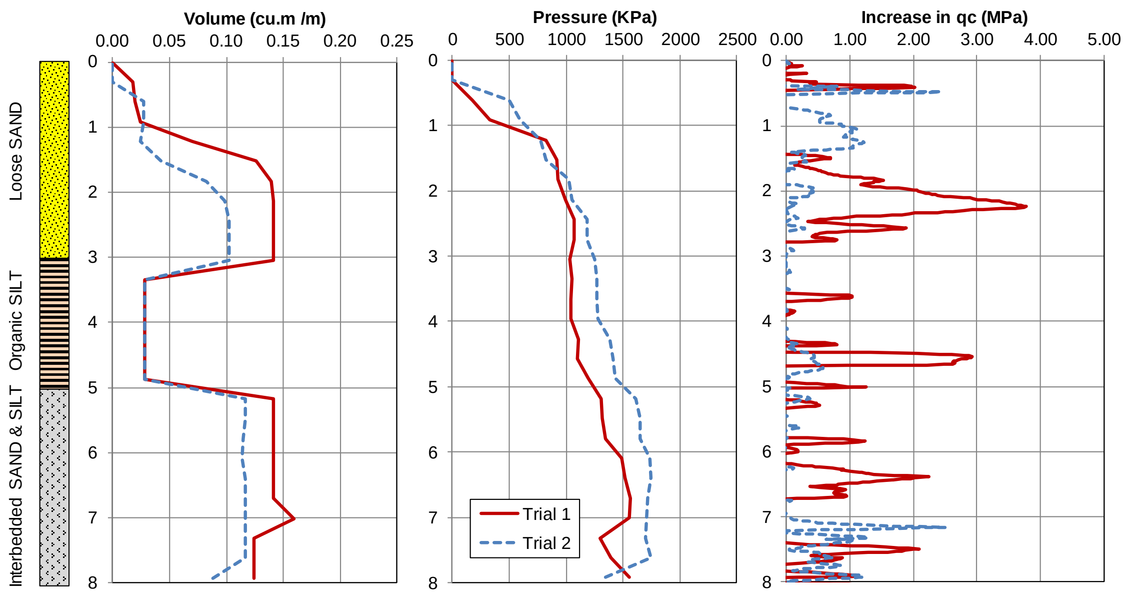


**Figure 2: LMG Trial Results**

The "increase" in cone resistance, qc is measured by way of a reference CPT close to the trial area but 5.0m from the nearest injection point. Whist the variability of the soils impacts on the results, Figure 2 indicates that a higher level of improvement is realised where the injection volume is greater. Furthermore, the increase in measured qc in the zone of the organic silts is very limited. The trial confirmed the optimum improvement possible could be achieved by targeting the upper and lower zones with up to 15% injection volume. However, the actual injection volume under the slabs would be restricted by the lift observed.

## 5 SLAB RE-LEVELLING WORKS

The slab re-levelling works were programmed within hospital during a Christmas shutdown period 2011. Some preparatory work was carried out prior to starting on 23/12/2011 but essentially 324 injection points and a total of 412 cu.m of grout was placed by 17/1/2012. On the 23/12/11 during the first day of grout placement the site was subject to a M6 seismic event; the REHS strong motion monitoring station recorded a horizontal pga = 0.35g. The site was evacuated and the structure formally assessed prior to re-entry and continuation of the works.

The same injection layout used in the trial was adopted for the main works with adjustment to suit the structure layout. The presence of walls and hospital M&E components required flexibility, careful planning and work in highly confined environment (Figure 3). A Primary and secondary injection regime was generally sufficient to re-level the slab in all but a small number of locations where tertiary injections were necessary to achieve the target lift.


**(a) Installing Casing** **(b) Grout Injection**


**Figure 3: LMG application within the hospital confines**

Given that the target slab lift required was in the range of 40mm to 150mm it was not envisaged that a uniform injection volume would be achievable across the slabs; the primary control mechanism was the lift achieved and not the volume injected. The slabs were successfully re-levelled but as shown in Table 1 the injection volumes are significantly less than the target value particularly when adjusted for the lift volume.

**Table 1: LMG injection volume assessment**

| Area Ref. | LMG Ratio Injected (%) | | | | Corrected LMG Volumes in Liquefiable zones | | | |
|---|---|---|---|---|---|---|---|---|
| | Primary | | Secondary | | Total LMG | Est. Lift | Nett | Ratio |
| | Upper | Lower | Upper | Lower | (m3) | (m3) | (m3) | (%) |
| A | 9 | 12 | 3 | 7 | 198.1 | 30.8 | 171.5 | 6.9 |
| B | 5 | 10 | 2 | 6 | 166.9 | 33.4 | 139.7 | 4.8 |
| C | 5 | 9 | 1 | 2 | 47.1 | 2.8 | 41.6 | 5.4 |
| D | 3 | 9 | | | 35.8 | 6.1 | 29.7 | 6.7 |

## 6 REVIEW OF CONSTRUCTION DATA

The same approach to the injection of LMG used in Trial 2 was adopted for the main works. Injection was targeted at potentially liquefiable upper zone at 1.0m to 3.0m depth and a lower zone from 5.0m to 8.0m below ground floor level. As can be seen in Table 1 there are clear trends with greater volumes in the lower primary injection points and the lowest volumes in the upper secondary points. From this data it is reasonable to conclude that:

- The depth and associated confining pressure results in greater injection volumes and lower surface expression
- The primary injection serves to increase the density of the adjacent soil, increasing the lateral resistance to secondary injection and promoting lift

There are three primary factors that can affect the grout injection volume possible given a limited lift; for this structure these are highlighted and discussed:

1. Soil type and state
   The density of loose to medium dense sands can be increased by the injection of LMG because they drain allowing volume change and the capacity to take up a volume of grout without significant heave. Soils that behave in an undrained manner, given the rate of pressure application, will simply be displaced by the injection of grout.

   The relatively clean sands in the upper 2.5m will be improved given sufficient confinement. However, the improvement of the non-liquefiable organic silt layer would not be expected so injection of grout would result in heave. The Inter-bedded sands and silts that extend to 8.5m are unpredictable in that the layer thicknesses, permeability and structure will determine the rate of drainage and thus whether densification occurs.

2. Variation in soil profile with depth
   The thickness and depth of liquefiable / non-liquefiable deposits impacts the volume of grout needed and what can be injected prior to excessive lift occurring.

   The pre-construction CPT data was located outside the building footprint and indicates the organic silt is present between 2.5m and 3.0m below ground level extending to 4.0m to 4.5m depth. The post-construction CPT data from within the building indicate these clays extend from 2.5m to 6.0m

3. Confinement
   The presence of a capping layer, structural slab or structural loading serves to resist upward movement of the soil thereby increasing the densification possible.

   With the structure supported on piled foundations the load on the slabs is very limited therefore confinement is limited to that provided by the mass of the slabs themselves.

Initial analysis of the CPT testing performed immediately after completion of the LMG re-levelling using CLiq v.1.5.1.26 Liquefaction Assessment Software. The SLS vertical settlement was calculated to be between 32mm and 56mm respectively (Figure 4). However, given the observed displacements resulting from a greater than ULS event were of a similar order the analysis was considered unacceptably conservative.

The calculations revealed that more than 50% of the settlement would occur in the upper sand layer between 1.5 and 2.5m depth based upon a ground water level at 1.0m depth. Site observations indicated the static ground water level was between 2.2 to 2.5m below ground level i.e. this layer is unlikely to liquefy. With the ground water level at 2.0m depth the resulting liquefaction settlement predicted is less than the 25mm design limit.

Furthermore, the methodology does not consider the effect of either the piles or grout inclusions in the ground when evaluating the liquefaction potential. Revised analysis adopting a Baez & Martin (1993) approach with a replacement ratio, Ar = 5% and shear stress reduction factor, Kg = 0.78 indicates the settlement would be less than 25mm for the design SLS seismic event.

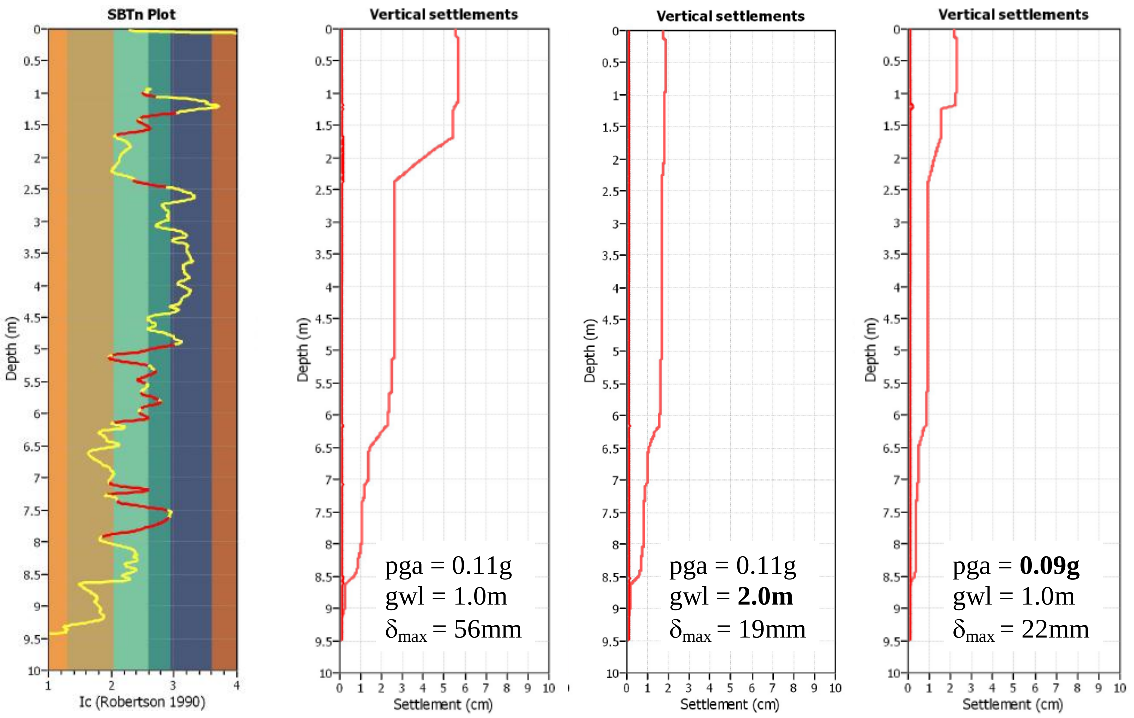


**Figure 4: Post LMG settlement evaluation**

Based upon the aforementioned the performance of the slabs under the M7.5, PGA = 0.11g seismic event is not expected to exceed the design settlement limit of 25mm.

## 7 CONCLUSIONS

Whilst the LMG process has now been more widely used in New Zealand, at the time this project was delivered experience was limited so considerable value was gained from the robust design and technical development process with input from experienced personnel based in the USA, Australia and New Zealand. It is imperative that a trial is performed if ground improvement is required because the response of the ground to LMG injection is affected by subtle changes in soil parameters and stratigraphy; the evaluation process is highly observational and experiential.

Given the soil type is a fundamental factor when considering potential improvement and lift during LMG injection Table 2 is presented as a simple guide based upon site observations. Essentially, the liquefiable Silts to Sands range can be improved with the silts likely to realise minimal improvement and the clean sands significant improvement.

**Table 2: Effect of LMG injection on soil types**

| | Effect of Low Mobility Grout | |
|---|---|---|
| Soil Type | Densification | Pore pressure |
| **Sands** | **Yes** | **No change** |
| **Silty Sands / Sandy Silt** | **Limited** | **Limited increase** |
| **Silts** | **Minor** | **Minor increase** |
| Clayey Silts / Silty Clays | None | Increased |
| Clays | None | Increased |
| Organic Clay / Silt | None | Increased |

Ground conditions at the site were variable and defined by data outside the building footprint. Typically this would be sufficient but it is clear that in this particular case the depth of potentially liquefiable material was less under the building and it is worth noting that the building loads could also affect the soil state. Given the additional CPT data within the building footprint the design grout injection volumes would have been re-assessed and targeted accordingly.

The surface expression and improvement achieved is also affected by the confinement afforded by the ground and, where present, the overlying structure. Further benefit can also be realised by adopting a primary and secondary injection point sequence.

The use of the LMG methodology to re-level and provide improvement was successfully applied in extremely constrained environment; it is difficult to imagine another methodology that could have achieved the same results given and timeframe and the limited functional disruption to the operation of hospital.

## 8 ACKNOWLEDGEMENTS

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