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# Jet grout columns operating as a reaction platform for Christchurch Art Gallery re-level uplift and soil liquefaction mitigation

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## ABSTRACT

The Christchurch Art Gallery, one of the most important buildings in Christchurch - New Zealand, suffered significant settlements due to the Canterbury Earthquake Sequence of 2010 and 2011.Relevelling of the building was undertaken to return it to its original level. The techniques employed to lift the building comprised the use of soil injection techniques, providing "*in-situ*" soil reinforcement with cementitious grout material and an increase in soil volume by soil fracture. This solution is known as JOG – Integrated Computer Grouting (JOGICG). This paper describes the adopted soil improvement solution beneath the existing building using jet grouting columns. This technique was used to provide an increase in soil stiffness and strength, ensuring sufficient soil reaction under the incremental stresses imposed by the JOGICG process during the structure uplifting works. In addition, jet grouting was considered to provide added value to the long term soil behavior with respect to soil induced liquefaction.

*Keywords:* Jet Grout, relevelling, ground improvement

## 1 - INTRODUCTION

The 2010 and 2011 Canterbury Earthquake Sequence struck the South Island of New Zealand causing significant damage, particularly in Christchurch, New Zealand's second largest city. Significant liquefaction of the underlying soils affected the eastern suburbs, as well as other parts of the city, generating around 400,000 tonnes of silt ejecta. The earthquake sequence resulted in loss of human lives, making it the second-deadliest natural disaster recorded in New Zealand. Extensive building and infrastructure damage also occurred. Governmental Authorities, together with the geotechnical community, are presently developing and implementing plans to strengthen and repair existing structures and rebuild those which were severely damaged or had collapsed. The Christchurch Art Gallery was one of the major civic buildings affected by the earthquake sequence, suffering total and differential settlements of up to approximately 150mm.

The relevelling solution to restore the pre-earthquake building levels comprised the use of the JOG Integrated Computer Grouting technique (JOGICG), in conjunction with a ground strengthening solution using jet grout columns (JG). The columns were formed in the upper sandy/gravel layer immediately beneath the basement floor of the Art Gallery building, to form a reaction platform for the JOGICG.

## 2 - INTRODUCTION

### 2.1 Building Location & Building Layout

The Christchurch Art Gallery is located between Montreal Street to the west, Gloucester Street to the north and Worcester Boulevard to the south. The building does not abut directly with any other building or structure. The surrounding area is characterized by open space and public roads, thus the proposed sub soil works would not interfere with other structures. The building comprises a multi storey, partially glass curtain wall clad structure positioned on the eastern side of the site. It is underlain by a single level basement carpark that extends across much of the site footprint, including beneath the plaza area between the main building and Montreal Street on the western boundary. The northeastern corner of the basement is occupied by a live electricity supply substation belonging to the city electricity supply company, which had to remain live throughout the relevelling works.

## 3 - GROUND CONDITIONS

### 3.1 Ground Investigation

Data from existing and supplementary ground investigation undertaken at relevel design stage was combined, allowing an improved understanding of the geological and geotechnical conditions at the site. The supplementary investigation comprised of cone penetration tests (CPT) external to the building to reach the underlying 'Riccarton Gravels' formation; three machine boreholes to approximately 10 m depth within the basement of the building; three CPT's from the base of the boreholes to extend to the 'Riccarton Gravels' and three CPT's from basement level until refusal. The groundwater level beneath the basement was monitored using a single standpipe piezometer installed in a borehole through the basement floor.

The external CPT's using a 22 Tonne Lankelma truck mounted rig (Figure 1) were able to punch through the upper gravelly soils and investigate the full depth down to the 'Riccarton Gravels'. Within the basement, the drilling was able to recover continuous samples of the gravelly soils beneath the basement floor and allowed visual evaluation of the gravel content of this layer. This predrilling to the base of the higher level gravel soils enabled cone penetration testing of the deeper sand stratum within the basement footprint using a portable CPT rig (Figure 1). Dissipation tests were performed in low permeability layers. The boreholes were drilled using a sonic head drilling rig.

*Figure 1. CPT truck (left) and portable CPT rig operating from the basement of the building (right).*

### 3.2 Sub-surface Conditions

3.2.1 Stratigraphy

The interpretation of the exploratory holes suggests that sand with gravels and very dense gravelly soils are overlying sandy soils; this lower layer is interspersed with silt/clayey silt layers. A clayey silt and a sandy silt layer immediately overlays the 'Riccarton Gravel', reached at approximately 24 m depth. The sequence encountered is represented in Figure 2 and described in more detail in Table 1.

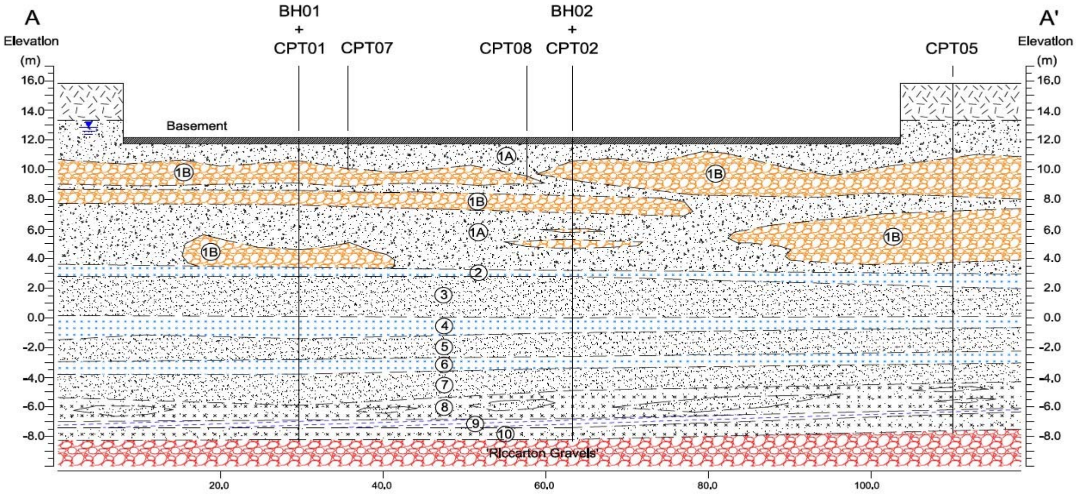

*Figure 2. Geological Cross-Section*

*Table 1: Sub-surface conditions*

| Geotechnical Unit | | Base* (m) | Thickness (m) | Description |
|---|---|---|---|---|
| Made Ground | | 2.5 – 2.6 | 2.5 – 2.6 | Sand, silt, gravels, construction spoils |
| 1A | Sand with gravels | 11.0 – 13.0 | 8.5 - 10.5 | Layer of sands with dispersed gravels, medium dense to dense and very dense sandy gravels |
| 1B | Sandy Gravels | | | |
| 2 | Silt/ Clayey-silt | 11.5 – 13.7 | 0.5 – 0.7 | Very loose to loose silt with trace of clay |
| 3 | Sand/Silty-sand | 15.0 -15.8 | 2.0 - 4.2 | Dense to very dense sand or silty-sand |
| 4 | Silt/ Clayey-silt | 16.5 – 17.2 | 0.8 – 1.5 | Very loose to loose silt with trace of clay |
| 5 | Sand/Silty-sand | 17.8 - 18.4 | 1.0 – 1.7 | Medium dense to very dense sand or silty-sand |
| 6 | Silt/Clayey-silt | 18.6 - 19.2 | 0.6 – 1.0 | Very loose to loose silt with trace of clay |
| 7 | Sand/Silty-sand | 20.1 – 21.6 | 1.5 – 2.5 | Medium dense to dense sand or silty-sand |
| 8 | Sandy-silt | 21.9 - 22.6 | 1.0 – 2.0 | Loose to medium dense sand and sandy-silt |
| 9 | Clay/Silty-clay | 22.6 - 23.2 | 0.3 - 0.6 | Firm to stiff clay or silty-clay. |
| 10 | Sandy-silt | 23.4 – 24.0 | 0.8 – 1.2 | Loose to medium dense sandy-silt |
| 'Riccarton Gravels' | | Unknown | Unknown | Typically 'very dense sandy gravels' |

* *Base of unit is below ground level external to the building and its basement*

3.2.3 Groundwater

Piezometer standpipes were installed in the external cone penetration test holes and within the basement. These were subsequently monitored relative to the basement level of RL 11.9 m. The standing water level was found to be between RL12.9 m and RL12.6 m. A dewatering scheme was operating through all stages of the relevelling works and so, for design purposes, the groundwater level was considered coincident with the underside of foundation slab.

## 4 - METHODOLOGY FOR BUILDING RELEVELLING

### 4.1 Introduction

The building relevel solution adopted to achieve the required levels for the building comprised the use of JOGICG, in conjunction with a ground strengthening solution using jet grout columns (JG) in the upper sandy/gravel layer beneath the basement floor. The ground strengthening was required to form a reaction platform. This solution was selected for its ability to operate cleanly and effectively within the low headroom basement carpark environment. Penetrations through the floor slab could be limited to 200 mm diameter for the installation of the JG columns and 40 mm diameter for the JOG injectors.

### 4.2 JOG Integrated Computer Grouting (JOGICG)

The JOGICG technique is an integrated computer-controlled grouting levelling method that manipulates grout rheology, controls the viscosity, fluid state, setting and cures times of its range of injected cementitious jacking grouts. As a consequence, it can control the ability of the grout to permeate the soil and allows control of the generated uplift force acting directly against the underside of the structure / foundations. The uplift is achieved by soil fracture (injection of grout at high pressure). Sequential injection at multiple locations greatly reduces the single point energy required to overcome the initial structure inertial forces and allows a continuous, balanced, controlled and gentle lift over large areas. Injection of grout with a suitable viscosity enables the formation of multiple thin grout layers beneath the building foundation. As the initial grout sets, new grout is injected and flows over the previous grout layer, resulting in lift; successive injection of grout creates layers which build up progressively in a random radial and laminar manner.

The computer control allows opening and closing the injection needles to provide different amounts of lift across the building. The process will form a more or less uniform grout material layer of approximately 0.5 m thickness before lifting of the building as a result of the permeation of the cementitious grout throughout the soil below the basement slab. Grout injection is than continued until the required lift for the building is met.

### 4.3 Jet Grouting

Jet grouting uses a high kinetic energy jet of cement slurry to break up and loosen the local ground, and form a mix of the ground and the slurry. This hydrodynamic mix-in-place technique produces a soil-cement material, commonly referred to as a jet grout column.

Jet grouting makes use of three physical processes, singly or in combination: the high energy jet loosens the soil; the jetting fluid washes some of the soil to the surface; the slurry adds a binder to the soil mix. During jetting, material in excess of the soil cement mix must rise freely to the injection collar, in order to prevent the excess material fracturing and disturbing the surrounding ground. The excess grout slurry is removed at a rate to ensure excess pressure does not build up in the fluid column being formed. The final resulting jet-grout columns (diameter, composition and strength of the columns) are dependent on drill string rotation and raising speeds, jet pressure and flow, grout mix, soil type, grain size distribution, composition and compactness and nozzle configuration, among others. Figure 3 shows the jet grouting columns being installed in the basement of the building.

*Figure 3. Installation of jet grouting columns in the Art Gallery basement*

## 5 - GROUND STRENGTHENING SOLUTION TO FORM REACTION PLATFORM

### 5.1 Introduction

The ground strengthening process comprised the installation of 3.0 m diameter jet grout columns, with a distance between columns of 7.50 m, set in a triangular grid pattern. Due to site and structural constraints, this grid was locally modified. In order to improve the stiffness of the reaction platform at the edges, the jet grout column diameter was increased to 4.0 m around the perimeter of the building.

The depth to the top of the jet grouting columns was designed to allow a load transfer layer between the raft foundation of the building and the top of the columns. This optimized the stress distribution and provided partial transfer of load directly to the jet grouting elements.

The columns were installed from within the existing car park basement, and were formed within the stiff layer characterized by sands and gravels (unit 1A/1B). The design length of the JG columns was 4.0 m, with the top and bottom of the columns positioned 2.50 m and 6.50 m below the underside of the basement slab respectively.

### 5.2 Design Calculations

Calculations were undertaken using the finite element analysis programs – PLAXIS 2D and PLAXIS 3D FOUNDATION. The structure geometry was simulated on a 15 node plain strain model and soil properties were defined using the *Hardening Soil Model*.

PLAXIS 2D analysis of a section through the length of the building (approx. 90 m) enabled simulation of the overall behavior of the treated ground. In order to confirm the results obtained in the 2D model, and to analyse the soil behavior in a representative treatment area in the interior of the building footprint, additional three dimensional analyses were carried out using PLAXIS 3D.

Soil behavior was modeled taking into account the stiffness and strength of the soil layers under an imposed vertical stress corresponding to the building loading. Immediately beneath the slab, a grout treated layer (JOGICG) of 0.50 m thickness was introduced; this being the zone into which it was predicted that the grout would penetrate. A soil volume increase, corresponding to the maximum uplift value of 0.15 m, was simulated using soil volume expansion, enabling the simulation of the grout injection. The JOGICG grout layer was confined to between the foundation slab and the soil. Taking into account the structure loading above the JOGICG layer as well as the stiffness of the soil, it was possible to determine the deformation transmitted to the structure and to the soil.

The deformation of the underlying soil due to soil volume expansion during the relevelling process leads to an increase in the imposed ground stresses. Knowing the magnitude of the incremental stress imposed on the soil, it was possible to analyse the maximum load transmitted to the jet grout columns and to calculate the corresponding deformation, confirming the adequacy of the ground improvement solution.

5.2.1 Immediate Settlements

The results obtained show that the volume expansion of the JOGICG grout layer leads to a ‘positive’ deformation (lift) of the foundation slab of about 0.15 m, as required. The deformation transmitted into the ground is almost non-existent (5 mm) and settlements are considered to be negligible. Nevertheless, it is considered that any settlement at this stage is offset by the JOGICG levelling process. The deformed finite element mesh for the 3D model and the calculated soil deformations after JOGICG and soil improvement with JG columns are presented in Figure 6.

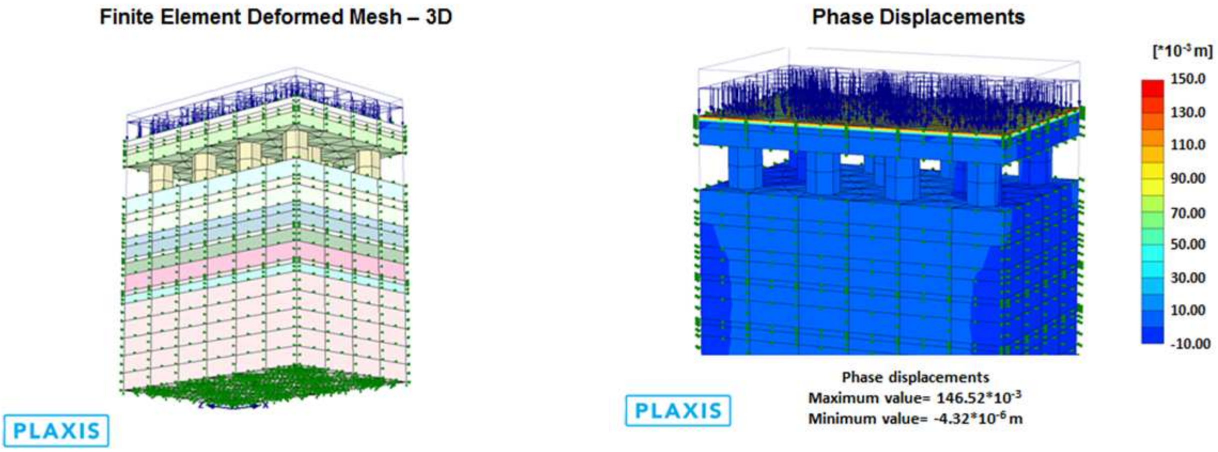

*Figure 4. 3D model finite element mesh (left) and deformations after JOG and jet grouting columns (right).*

5.2.2 Effective Vertical Stresses

The vertical effective stresses on the soil were evaluated at a depth of 1.20 m below the slab level, i.e. 1.30 m above the top of the jet grout columns. This level is considered to provide representative stresses imposed on the jet grout columns and surrounding soil due to the JOGICG works.

A maximum initial effective vertical stress before JOGICG works and JG installation of $\sigma'_y$=126 kPa was determined. The PLAXIS 2D analyses calculated a maximum effective vertical stress of $\sigma'_y$=180 kPa immediately after the building uplift. Effective vertical stresses transmitted to the ground are presented in Figure 5. The incremental vertical effective stress imposed into the ground due to JOGICG works thus corresponds to $\Delta\sigma'_y$=180-126=54 kPa.

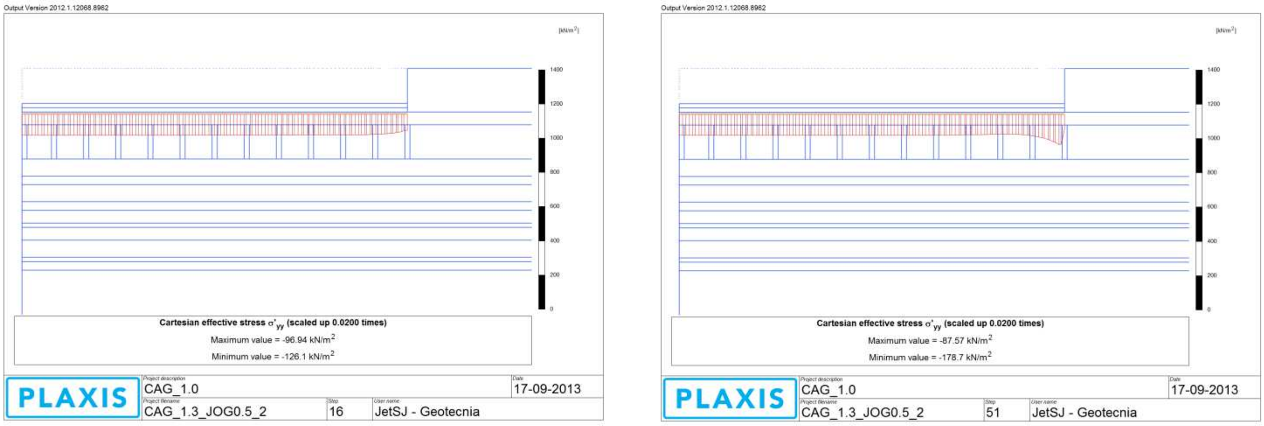

*Figure 5. Maximum effective vertical stress before JOGICG works (left) and after (right).*

### 5.2.2 Long Term Settlements

Long term settlements were calculated using consolidation characteristics of the low permeability soils beneath the building (Geotechnical Units 2, 4, 6 and 9 referred in Table 1). The consolidation analysis was based only on the incremental stress of 54 kPa imposed by the JOGICG works and determined a long term settlement of 18 mm. The estimated time for the pore water dissipation (primary consolidation) on the low permeability soil layers was estimated to be of the order of 1 month, with most of the settlement occurring in the first 10 days.

## 6 - SOIL INDUCED LIQUEFACTION MITIGATION

### 6.1 Introduction

The relevel works are expected to provide the existing building with improved behaviour under seismic loading by the creation of a stabilized crust to 6.5 m depth below the base of the foundation base reducing the predicted settlement induced by soil liquefaction.

The JG columns provide a zone of ground improvement that will reduce soil shear strains during seismic events (due to stress concentration) and therefore reduce the severity of liquefaction within the treated zone. The stress concentration reduction factor from soil improvement by the JG columns ($K_g$) was determined in accordance with the H. Turan Durgunoglu (2004) formulation. Assuming that the ratio of the jet grout column shear modulus ($G_{JG}$≈400 MPa - considering a minimum unconfined compressive strength of 2.2 MPa for JG columns) and the shear modulus of the soil ($G_S$≈40 MPa - estimated from the CPT results on site) is in the order of 10, and that the JG replacement ratio is 19.6 %, a reduction factor of Kg=0.36 is obtained.

In order to estimate the potential for soil liquefaction, the ratio of the Cyclic Resistance Ratio (CRR) to the Cyclic Stress Ratio (CSR) was determined. In the JG column area, the original CSR values were reduced by the calculated shear stress reduction factor ($K_g$=0.36). The seismic design requirements adopted for use in the analyses were:-

- NCEER's calculation method (modified for fines content);
- magnitude M7.5 EQ event;
- peak ground acceleration of 0.20 g (for annual exceedance probabilities of 1/150 – SLS.

Liquefaction analyses were undertaken using the software 'CLiq'. While the upper soil layers (Units 1A and 1B) may be considered generally as non-liquefiable, thin liquefiable layers still exist within the sandy soils (1A) and between the gravel layers (1B). The ground improvement will mitigate liquefaction in these layers under the considered SLS event. Figure 6 shows an overlay of the potential liquefiable layers based on the available CPT data, and the effect of the ground improvement in mitigating the liquefaction potential under the considered SLS event.

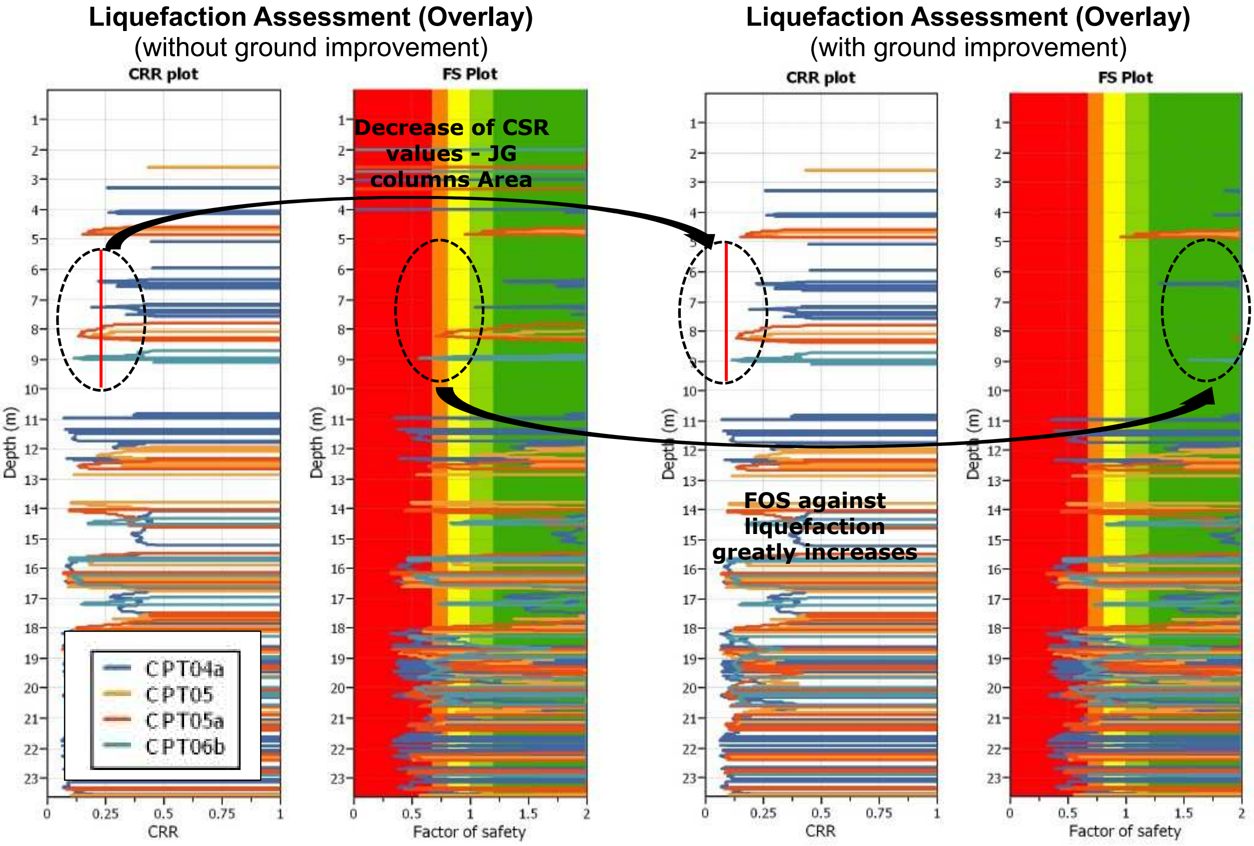

*Figure 6. Liquefaction assessment overlay of CPT's 4a, 5, 5a and 6b.*

One of the main reasons for the observed differential settlement of the structure was considered to be the liquefaction of shallow soils below basement. Professor Ishihara (Kenji Ishihara, 1985) collected data from numerous case studies where he showed that there is an inverse relation between the thickness of a non-liquefiable soil mantle and the liquefaction damage observed at the ground surface. The Ishihara charts (Figure 7) show that a non-liquefiable crust of 3 m thick is sufficient to limit the expected liquefaction induced ground damage under a SLS event of 0.2 g and M7.5.

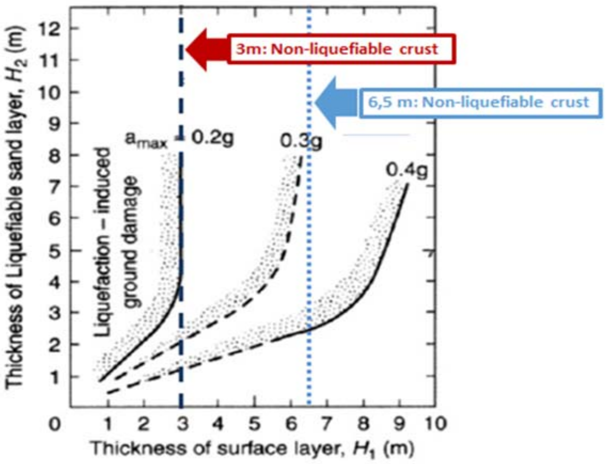

*Figure 7. Boundary curves for site identification of liquefaction-induced damage (Ishihara 1985)*

The relevel solution provides an obvious added value by improving the behavior of the structure under future seismic events. This conclusion is based on the assumption that a non-liquefiable crust has the benefit of mitigating the effects on the structure of deeper liquefaction induced settlements. Global settlements are expected to occur under a seismic event but were considered to be tolerable and the effects on surface structures should be non-damaging.

The relevel solution of the Christchurch Art Gallery provides a non-liquefiable crust to a depth of at least 6.5 m below the foundation slab, which is considered sufficient to minimize liquefaction damage at foundation level. While liquefaction will still occur deeper in the underlying soils where we identified the most liquefiable prone material, experience during past earthquakes shows that, under SLS seismic loading, these are likely to be non-damaging to the structure.

## 7 - CONCLUSION

The analyses, design and subsequent relevelling of the Christchurch Art Gallery building have highlighted the following advantages on the use of JG columns as a JOGICG reaction platform:-

- After ground strengthening with JG columns and relevelling of the building using JOGICG techniques, the calculated immediate settlement on the ground is about 5 mm, corresponding to an additional local stress on the ground of approximately 54kPa. It is considered that any settlement at this stage is offset by the JOG levelling process.
- The low estimated ground deformations confirm the function of the JG reaction platform for JOGICG.
- The analyses determined a long term settlement of 18 mm with an estimated time for the pore water dissipation (primary consolidation) in the low permeability soil layers in the order of 1 month, with most of the settlement occurring in the first 10 days.
- Added value in the form of improved resistance to soil liquefaction occurs due to stress concentration on the jet grout columns. This, together with soil densification, will create a non-liquefiable crust of at least 6.5 m thickness below the building foundation during a seismic event of 0.2 g and M7.5.
- The non-liquefiable crust formed by the JG process is considered to be sufficient to minimize the liquefaction damage at foundation level during an SLS level event.

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