Jet Grout Columns Operating As A Reaction Platform For Christchurch Art Gallery Relevel Uplift And Soil Liquefaction Mitigation

A.Nogueira¹, A.Cristovao², A.Pinto³, R.Hutchison⁴, W.Lindsay⁵

ABSTRACT

The Christchurch Art Gallery, 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 and compaction grouting. These techniques were 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 and compaction grouting was considered to provide added value to the long term soil behavior with respect to soil induced liquefaction.

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. 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) and compaction grouting to form a reaction platform for the JOGICG.

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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.

Ground Conditions

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 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. Dissipation tests were performed in low permeability layers. The boreholes were drilled using a sonic head drilling rig.

Sub-surface Conditions

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 1 and described in more detail in Table 1.
Table 1- Sub-surface conditions

<table>
<thead>
<tr>
<th>Geotechnical Unit</th>
<th>Base* (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made Ground</td>
<td>2.5 – 2.6</td>
<td>Sand, silt, gravels, construction spoils</td>
</tr>
<tr>
<td>1A Sand with gravels</td>
<td>11.0 – 13.0</td>
<td>Layer of sands with dispersed gravels, medium dense to dense and very dense sandy gravels</td>
</tr>
<tr>
<td>1B Sandy Gravels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Silt/ Clayey-silt</td>
<td>11.5 – 13.7</td>
<td>Very loose to loose silt with trace of clay</td>
</tr>
<tr>
<td>3 Sand/Silty-sand</td>
<td>15.0 -15.8</td>
<td>Dense to very dense sand or silty-sand</td>
</tr>
<tr>
<td>4 Silt/ Clayey-silt</td>
<td>16.5 – 17.2</td>
<td>Very loose to loose silt with trace of clay</td>
</tr>
<tr>
<td>5 Sand/Silty-sand</td>
<td>17.8 - 18.4</td>
<td>Medium dense to very dense sand or silty-sand</td>
</tr>
<tr>
<td>6 Silt/Clayey-silt</td>
<td>18.6 - 19.2</td>
<td>Very loose to loose silt with trace of clay</td>
</tr>
<tr>
<td>7 Sand/Silty-sand</td>
<td>20.1 – 21.6</td>
<td>Medium dense to dense sand or silty-sand</td>
</tr>
<tr>
<td>8 Sandy-silt</td>
<td>21.9 - 22.6</td>
<td>Loose to medium dense sand and sandy-silt</td>
</tr>
<tr>
<td>9 Clay/Silty-clay</td>
<td>22.6 - 23.2</td>
<td>Firm to stiff clay or silty-clay.</td>
</tr>
<tr>
<td>10 Sandy-silt</td>
<td>23.4 – 24.0</td>
<td>Loose to medium dense sandy-silt</td>
</tr>
<tr>
<td>‘Riccarton Gravels’</td>
<td>Unknown</td>
<td>Typically ‘very dense sandy gravels’</td>
</tr>
</tbody>
</table>

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

Methodology for Building Releveling

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 JG columns 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. Where due to site constraints were not possible install JG columns, compaction grouting was used as a soil strengthening technique.
**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 cure 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. 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.

**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. 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.

**Ground Strengthening Solution to Form Reaction Platform**

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, and in two specific locations compaction grouting was used instead of jet grout columns. 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 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.

**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 deformation of the underlying soil due to soil volume expansion during the relevelling process leads to an increase in the imposed ground stresses (Figure 2). Knowing the magnitude of the incremental stress imposed on the soil, it was possible to calculate the corresponding deformation of the soil, confirming the adequacy of the ground improvement solution.

Figure 2 – Uplift, Incremental Stress and load distribution.

**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 3.

Figure 3 – 3D finite element mesh (left) and deformations after JOGICG and JG columns (right).
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. The incremental vertical effective stress imposed into the ground due to JOGICG works thus corresponds to $\Delta \sigma'_y=180-126=54$ kPa.

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.

Soil Induced Liquefaction Mitigation

The ground strengthening works are expected to provide the existing building with improved behavior under seismic loading reducing the predicted settlement induced by soil liquefaction.

To prove the seismic improvement behavior of the soils, a crosshole seismic shear-wave and MASW surveys were conducted to compare the shear-wave velocities in the near surface from before and after the ground strengthening works. In Figure 4 is shown the geophysical investigation locations before and after the ground strengthening works (Phase 1 & Phase 2 respectively).
The cross-hole survey was undertaken between BH1 and BH2 and between BH1 and BH3 in an area where jet grout columns were not possible to be installed and replaced by compaction grouting. Results from crosshole survey show a clear increase in shear-wave velocities between the two surveys, confirming an improvement of the soil resistance under seismic loading. The obtained results are shown in Figure 5.

The MASW data showed lower quality due to contamination from background noise and artefacts created by high velocity waves passing through the concrete slab and building foundations, however, the bulk shear-wave velocity values between Phase 1 and Phase 2 show a general increase with a few areas showing a marked increase. The shear-wave velocity measurement for each phase and the absolute value of change in bulk shear wave velocity is shown in Figure 6.
Conclusions

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

- The low estimated ground deformations confirm the function of the JG reaction platform for JOGICG releveling works.
- 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.
- A crosshole seismic shear-wave and MASW surveys conducted to compare the shear-wave velocities in the near surface from before and after the ground strengthening works showed generally a clear increase.
- This proved an added value in the form of improved resistance to soil liquefaction due to soil strengthening by JG columns installation and compaction grouting, reducing the liquefaction potential and the damage at foundation level after a seismic event.

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