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Jet grout column construction and quality controls for seismic strengthening Auckland's waterfront

Construction et contrôles de colonnes de jet grouting pour le renforcement sismique d'un quai à Auckland

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ABSTRACT: The Quay Street Seismic Strengthening project was part of Auckland Transport's (AT) wider Downtown Infrastructure Development Programme (DIDP), which aimed to prepare downtown Auckland for the America's Cup and Asia-Pacific Economic Cooperation events in 2021. Previous seismic assessments of the seawalls that support Quay Street have shown that they are vulnerable to liquefaction/cyclic softening induced lateral spread. Seismic strengthening was proposed to provide seismic resilience to Quay Street for the next 100 years, providing post-disaster functionality for transportation services and protecting essential utilities located landward of the proposed strengthening alignment. To carry out the project, the Quay Street seawall was divided into four sections, with different strengthening solutions proposed in each section and each of the sections being constructed as standalone projects. This paper focuses on the westernmost section adjacent to Princes Wharf where jet grout columns were installed to form a shear wall in the Quay Street road reserve, landward of the existing seawall. After a description of the jet grouting works is provided along with challenges faced during construction, the quality controls implemented on site are specifically highlighted. Comparative results of tests done on both wet grab and core samples are presented, as well as non-destructive controls by acoustic and optic televiewer inside the coreholes. The relevance of the use of evaluating criterion such as Rock Quality Designation (RQD) or Core Improvement Rate (CIR) for jet grouting works will also be discussed.

RÉSUMÉ : Le projet de confortement de Quay Street fait partie d'un large programme de développement urbain à Auckland, dans l'objectif de préparer la ville à recevoir deux évènements majeurs en 2021 : la Coupe de l'América et le Forum Economique Asie-Pacifique. L'analyse du comportement du mur de quai supportant Quay Street a récemment montré une vulnérabilité face aux sollicitations cycliques. Le Projet vise à conforter ce quai de manière à protéger les voies de circulation et protéger les structures existantes face aux conséquences d'un séisme pour le prochain siècle. Le long du tracé, quatre différentes zones de quai ont été identifiées, chacune faisant l'objet d'un renforcement différent, et traitée séparément. Cet article se focalise sur la zone la plus à l'Ouest du Projet, pour laquelle la technique de confortement retenue a consisté à construire des refends constitués chacun de plusieurs colonnes de jet grouting sécantes. Après avoir évoqué le détail des travaux réalisés, on se focalisera sur les contrôles qualité menés pendant l'exécution. Nous aborderons notamment la comparaison des résultats obtenus sur carottes et échantillons de spoil, complétée par des contrôles par caméra de forage dans les sondages carottés. Enfin, nous aborderons la pertinence de l'utilisation de critères de type RQD ou CIR pour caractériser le matériau sur ce Projet.

KEYWORDS: Jet-grouting, seismic strengthening, quality controls, core sampling, rock quality designation

1 INTRODUCTION : THE PROJECT

The Quay Street Strengthening Project was related to the upgrade of the existing Quay Street seawall, which forms the harbour edge of historic reclamation in downtown Auckland. The seawall supports Quay Street and the services contained within the road corridor as well as providing connection between Downtown Auckland and the adjacent wharf and port infrastructure.

Previous work by Tonkin & Taylor Ltd. (T+T) established that the existing seawall did not meet current design standards. Some sections of the seawall were also due for repair and maintenance. This project also provided the opportunity to design for the future climate and changing use patterns, particularly the impacts of ship propeller wash as ferry and cruise ship operations changed their locations and intensified their activities.

Auckland Transport (AT) proposed to upgrade the existing seawall to strengthen Quay Street and improve seismic protection for the assets supported by the wall, address general maintenance needs, and build resilience for future use of the harbour.

To achieve the seawall upgrade within the required timeframes, as well as provide a robust and cost-effective solution, respective seawall design options were proposed for each zone. The proposed typical solutions for the sections were:

- Princes Wharf – Jet grout columns landward of the existing seawall within Quay Street road reserve;
- Ferry Basin –Anchoring of the existing seawall and applying shotcrete facing where necessary;
- Ferry Building – Palisade wall and/or anchoring of the existing seawall;
- Queens Wharf to Marsden Wharf – Palisade wall landward of the existing seawall within Quay Street road reserve.

This paper focuses on the construction of the westernmost section adjacent to Princes Wharf where jet grout columns were installed to form shear walls landward of the existing seawall. Challenges faced during construction are described, with a highlight on the quality controls implemented on site.

2 DESIGN AND CONSTRUCTION

2.1 *Geotechnical conditions*

The Ground Conditions Report (T+T, 2019b) provided site-wide details on the ground conditions for the Quay Street Strengthening Project. This included information on published geology, and the geological model for the site including geological units. The relative position of jet grouting columns within the geological units is presented in figure 1. A short description of the geological units is given in Table 1.

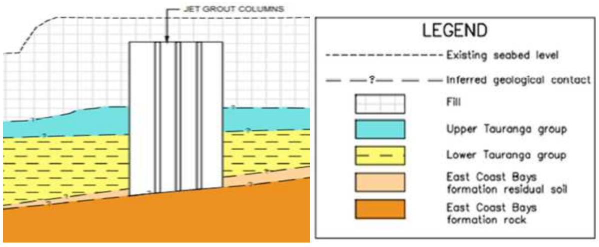

Figure 1: Jet grout columns within the geotechnical units of the site.

Table 1 : Short description of site lithography

Layer name	Soil type	SPT N-value
Fill	Soft to firm silty clay, Clayey silt, Very loose to loose silty sand	0 -14
Upper Tauranga Group	Interbedded very loose to loose silty fine sand and very soft clayey silt.	0-4
Lower Tauranga Group	Stiff to very stiff clayey silts / silty clays very loose to medium dense silty sand. Very dense sand with boulders	- 0-30 >45
ECBF Residual	Medium dense to dense sand with variable silt content.	30-50
ECBF Rock	Slightly weathered to unweathered interbedded sandstone and siltstone	>50

2.2 *Jet-grouting design*

Jet grouting is a construction technique that uses a high-pressure jet of fluid to break up and loosen the soil at increasing depths in a borehole. The jet of fluid is a water and cement mixture that mixes with the in-situ soil to form hardened columns in the ground.

The parameters for the jet-grouting process to achieve the required final strength and diameter depend on the following factors:

- The geotechnical properties of the soil to be treated;
- The radius and strength of the jet required to achieve the required size of the hardened columns;
- The required mechanical post-treatment soil properties Site constraints and its environment.

On this project, both the arrangement of the jet-grouted columns and the design parameters were initiated during an Early Contractor Involvement (ECI) phase where the contractor and designer worked collaboratively to establish the final design solution.

The detailed design for the Princes Wharf Zone of the Quay Street Strengthening Project comprised rows of overlapping jet grout columns forming a shear wall landward of the existing seawall, extending approximately 110 m along the Quay Street road reserve.

A typical row within the shear wall was formed of four jet grout columns at maximum 1.2 m centre-to-centre spacing and comprised one 1.7 m diameter seaward column and three 1.4 m diameter landward columns, as shown on figure 2.

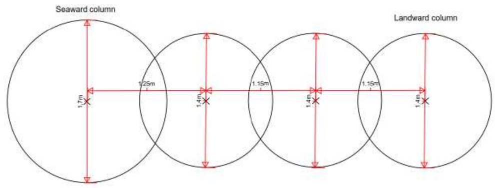

Figure 2: Jet grout columns within the geotechnical units of the site.

The average overlap contact width between the columns adopted for design was 500 mm with a minimum of 300mm based on a maximum allowable verticality deviation of 0.5%.

The columns were designed to the top of ECBF rock . The Target Soil Stabilisation Extent comprised all in-situ material 2 m depth below ground surface down to 0.3 m the top of below ECBF rock level such that the jet grout column forms a clean contact with the rock with no significant soft soil present at the contact.

Along the Quay Street road reserve, rows of columns were designed to be at 3 m centre-to-centre spacing in a direction parallel to the existing seawall, forming an improved soil block. For calculation purposes, geotechnical parameters of this soil block were determined by calculating the area weighted average of the strength of jet grout columns and that of the soil mass, through an area replacement ratio (ARR).

The key geotechnical design considerations for the works included:

- 100-year design life criteria, resulting in a magnitude 5.9 earthquake and ultimate limit state (ULS) peak ground acceleration (PGA) of 0.28 g;
- Isolated lenses of Reclamation Fill and Upper Tauranga Group (UTG) sands considered susceptible to liquefaction, with the remaining UTG material considered susceptible to cyclic softening during seismic events;
- Design groundwater levels adopted for design considered both high and low tide levels.

A finite element analysis was undertaken to confirm the overall performance of the jet-grout block, with a minimum required UCS strength of the columns of 8 MPa for the 1.7 m diameter seaward column and 6 MPa for the three landward 1.4 m diameter columns.

A last design stage was finally carried out, following an additional ground investigation campaign executed at the production stage together with the relaxation of the horizontal ground displacement requirements. The final proposed configuration allowed to reduce the tensile and shear forces applied to the jet grout block, which lead to readjust the target compressive strengths to 5 and 3 MPa, respectively.

2.3 *Execution of Jet Grouting works*

2.3.1 *Execution*

Columns were constructed in a primary-secondary sequence using the single fluid jet technique utilizing a patented optimized nozzle, operated for the second time in New Zealand.

Such device was described in former articles listed in the bibliography (Mathieu and al., Morey and al.). The execution conditions of jet grouting on site are illustrated on figure 3.

Figure 3: Execution of jet grouting columns on site.

The secondary column was increased to 1.7 m diameter over at least part of its height when quality assurance/quality control data for the primary columns showed that the design overlap width was unlikely to be achieved with a 1.4m diameter column.

The jet grout columns were located to minimize the impact on existing utilities, based on previous desktop studies and test pits undertaken by others. The location and configuration of the columns were designed to avoid damage to the existing utilities and where clashes remained the utilities were diverted or protected. PVC sleeves were installed in the end to end trench to facilitate jet grout column construction.

2.3.2 *Challenging geotechnical conditions*

During the execution of the jet grout columns, the JV faced challenging ground conditions, with the presence of a variable thickness of uncontrolled historic reclamation fill.

The material encountered during drilling (woods, steel, etc...) caused drilling difficulties such as partial or total losses of grout or columns put on hold due to the presence of obstructions.

Following the execution and analysis of jet grouting columns in three early production zones, further ground investigations were performed along the Princes Wharf section.

The objective of these investigations was to precisely map the position and thickness of the different soil and rock layers (fill, Upper Tauranga Group, Lower Tauranga Group, ECBF).

Further testing of the Lower Tauranga Group was undertaken during the production stage through SPT and shear vane tests, to assist with jet grout treatment of this layer.

The SPT values measured in the LTG inside the area to be treated were ranging from 6 to 50, with an average at 18. Undrained shear strength measured on further additional boreholes showed an average value of 140 kPa.

Both shear strength and SPT N values were significantly higher than initial assumptions. As formerly explained, the design was reviewed at that stage and the jet-grouting parameters were readjusted accordingly.

2.3.3 *Quality Assurance/Quality Controls*

During construction, drilling and jet grout parameters were logged in a data logger, monitored continuously and recorded. A construction report was produced for each column.

A verticality control report was provided with each construction report. The Shape Accel Array system was introduced inside the drill string at the end of the drilling phase. Figure 4 summarizes the deviation of the bottom of each column from a top view where the plain and dotted circles represent 0.5% and 1% verticality tolerances.

More than half of the drilling deviations were within the verticality tolerances of 0.5% specified in the project. Around 80% were within the typically accepted 1%. The presence of obstructions in the fill layer was the most probable source of the remaining deviations of these tolerances larger than 1%.

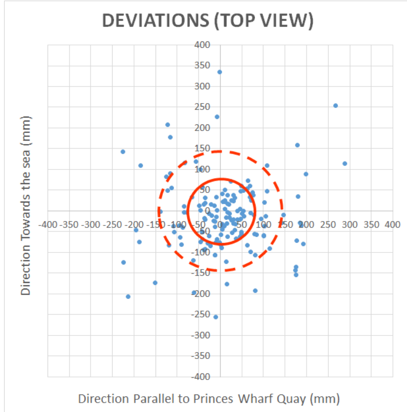

Figure 4: Column deviations (top view)

In addition to the testing required in the Jet Grouting Specifications, internal quality control was undertaken by the JV during construction, such as additional unconfined compressive strengths measured on grout cylinders, spoil cylinders, as well as viscosity and density tests on the cementitious grout.

Spoil cylinders were regularly taken from the outflow of soil cement material during jet-grouting. A set of 3 samples was taken at 2 different depths on each tested column. Figure 5 summarizes the unconfined compressive strength (UCS) values at 28 days measured on 54 columns during both trial and production stages.

Dispersion of UCS values was relatively usual for this type of works and related to the quantity of natural soil eroded, driven by variations of soil nature and compacity. Despite these dispersions, almost all values measured were above 8 MPa for the 1.7m diameter columns and 6 MPa for 1.4m diameter.

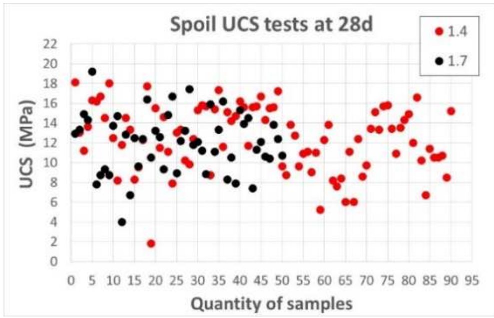

Figure 5: Unconfined compressive strength on spoil samples

At a further construction stage, core samples were taken from some hardened columns. The location of these cores was variable, from the center of columns to the edge. More than half of the samples were taken from the overlapping zone in between two adjacent jet grout elements.

Total core recovery (TCR) and Rock Quality Designation (RQD) values are discussed further in this paper.

Parts of these cores were extracted to carry out UCS testing in laboratory. Figure 6 below shows the UCS values measured on cores, presented with respect of the sampling depth. A red dotted vertical line indicates the minimum strength requirement for each type of column.

As seen on wet grab samples, UCS values were relatively scattered, but mainly above the minimum requirement for 1.4m diameter columns. For 1.70m columns, core samples were mainly taken from the overlapping zones which could be the source of a greater quantity of values below the minimum strength requirement.

Visual inspection of the samples taken from the cores showed a soil cement material of a relatively good quality, with some incl usions and sometimes a visible joint when the core was taken fr om the overlapping zone

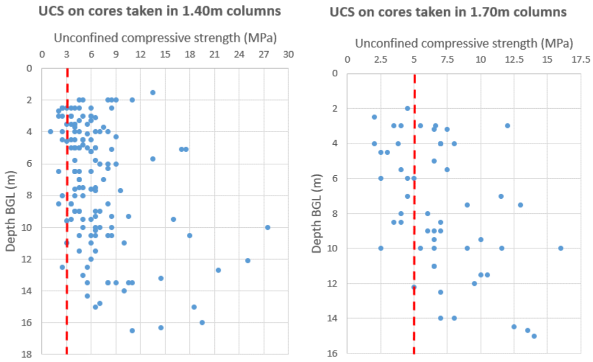

Figure 6: Unconfined compressive strength on cored samples

in between columns. A few examples are provided in figure 7.

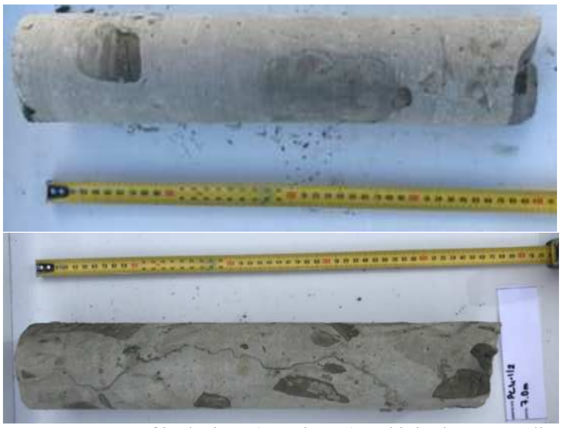
Figure 7 : Presence of inclusions (top picture) and joint between adjacent columns (bottom picture)

3 RESULT ANALYSIS

3.1 Wet grab samples vs core samples

A comparison between unconfined compressive strength on spoil samples and cored sampled was done. When available, values were compared for the same column, at similar sampling depth. Figure 8 below summarizes this comparison and shows that UCS on spoils was almost systematically of higher strength.

Considering the nature of the treated soils on site and accepting the absence of coarser elements in the spoil return, it was considered that both spoil and core sampled material were of similar nature and composition.

However, and as shown on figure 7, core samples comprised more coarse elements such as clay lumps or stones, and were subject to cracks linked to coring operations, or the location of the coring itself. This was a probable explanation of UCS values on cores being lower than expected.

3.2 *Non destructive controls*

As conclusions about the quality of the treatment was not obvious from the core results only, non-destructive controls were implemented inside some vertical coreholes done through the overlapping zone between two columns.

These non-destructive controls were done by downhole imaging with both optical and acoustic televiewer (OTV/ATV).

The optical tool gave a 360 degrees image of the borehole, whereas the acoustic tool provided another image of the borehole based on reflections of an acoustic signal on the borehole wall.

Both measures were correlated with depth and orientated to the magnetic North based on data measured by an embedded magnetometer in the tool. Figure 9 below gives a typical output provided by the televiewer.

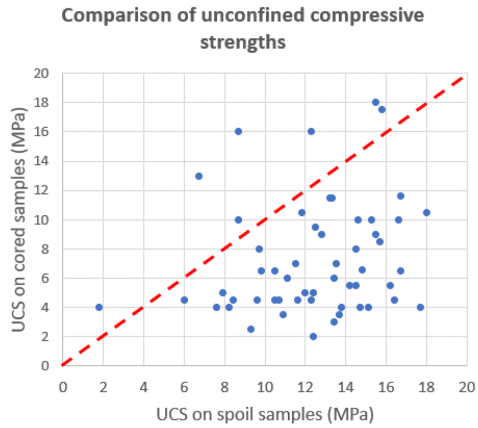

Figure 8 : Comparison between UCS on samples taken from coring or from spoil sampling.

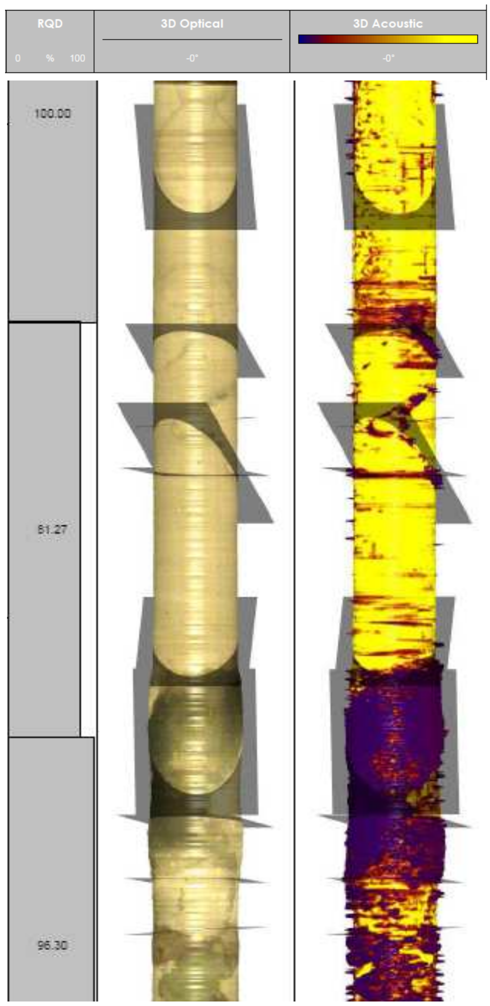

Figure 9 : Example of OTV/ATV readings in a vertical core done in the overlapping zone between columns.

OTV/ATV measurements allowed the treatment continuity between columns to be checked and particularly highlighted the presence of local micro fissures within the treated mass, localized on figure 9 by more or less inclined plans on both optical and acoustic 3D image of the borehole walls.

3.3 *About the use of RQD and CIR*

The specifications proposed an assessment of the quality of the overlaps of the columns based on the Total Core Recovery (TCR) and Rock Quality Designation (RQD). The requirement were minimum 90% and 50%, respectively.

However, the RQD target value could not be reached on this project.

It was believed that some of the cracks observed in the cores, which degraded the calculated RQD, were likely due to the coring process itself and were not reflecting the in-situ condition of the columns.

It was found that the RQD value may not be the most adequate value to consider and another notion of Core-Improvement Ratio (CIR) was introduced.

CIR, as explained in a paper from Yoshitake and al (2004)., allowed qualification of the jet grouting improvement in 5 levels based on the aspect of the cored sample.

It was found that CIR may be more relevant to qualify the quality of the overlap zone between adjacent jet-grouting columns, rather than the RQD value. However, the OTV/ATV measurements provided the most reliable means of assessing the in-situ quality of the jet grout treatment.

4 CONCLUSIONS

The use of jet grouting as seismic strengthening of the land adjacent to the seawall at Princes Wharf was a novel concept which proved to be effective.

The multiplicity of services at shallow depths and the small footprint needed at these shallow depths resulted in minimal clashes with services.

As for any jet-grouting project, a comprehensive investigation of the ground conditions as well as construction and analysis of trial columns before construction are keys for success.

During this specific case history, additional ground data gathered at construction stage allowed to revise the design and the strength requirement of the shear walls.

At production stage, the integration of ATV/OTV measures within the quality control program was particularly relevant to supplement the information collected through more conventional measurements.

5 ACKNOWLEDGEMENTS

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