THREE DIMENSIONAL MAPPING OF OVERLAPPING JET GROUT COLUMNS USED TO CONSTRUCT DEEP CUT OFFS AT LA ROMAINE 3

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ABSTRACT

La Romaine Hydroelectrical Complex Project is the largest construction project currently underway in Canada. The project comprises the construction of four new hydroelectric power generating stations and associated earth dams along the Romaine River in the Lower North Shore region of Quebec. The project is scheduled to be completed in 2020 with 1550MW total generating capacity; La Romaine 3 is the third phase of the project. The finished earth fill main dam will be 89m high and 300m wide at the base and will retain an 84km² reservoir.

Two temporary earth cofferdams were required to facilitate the construction of the main earth fill dam at La Romaine 3. Jet grouting using the double fluid process was performed to depths as great as 34 metres below surface to create low-permeability cut-off walls beneath the temporary upstream and downstream cofferdams. Several challenges pertaining to drilling conditions, soil conditions and variability of rock profile necessitated tailored and evolving drilling and grouting methodologies. Alignment surveying was performed on every jet grouted column using a three-dimensional mapping approach implemented to verify continuity of the cut-off. This quality assurance approach enabled the jet grouting contractor, General Contractor and Owner to identify areas of concern regarding potential “windows” requiring additional treatment due to alignment deviation.

The specified requirements for the low permeability cut-off wall were achieved by implementation of a comprehensive alignment survey program complemented by three-dimensional mapping. This paper outlines the details and evolution of the quality assurance program undertaken during construction of the jet grouted cut-off wall at La Romaine 3.

RÉSUMÉ

La Romaine hydroélectrique Projet de complexe est le plus grand projet de construction en cours au Canada. Le projet comprend la construction de quatre nouvelles centrales de production hydroélectriques et des barrages de terre associés le long de la rivière Romaine dans la région Basse Côte-Nord du Québec. Le projet devrait être achevé en 2020 avec 1550MW capacité totale de production; La Romaine 3 est la troisième phase du projet. La terre fini de remplir barrage principal sera 89m de haut et 300m de large à la base et conservera un réservoir 84km².

Deux batardeaux de terre provisoires ont été nécessaires pour faciliter la construction de la principale terre de remplissage barrage de La Romaine 3. Jet grouting utilisant le processus fluide à double a été effectuée à des profondeurs aussi grande que 34 mètres sous la surface pour créer à faible perméabilité des murs de coupure sous la batardeaux en amont et en aval temporaires. Plusieurs défis se rapportant à des conditions de forage, les conditions du sol et de la variabilité du profil de rock nécessitaient forage et d'injection des méthodologies adaptées et évolutives. Alignement arpentage a été effectué sur chaque colonne de jet injecté en utilisant une approche de cartographie en trois dimensions mis en œuvre pour vérifier la continuité de la coupure. Cette approche d’assurance de la qualité a permis au jet grouting entrepreneur, entrepreneur général et propriétaire d'identifier les domaines potentiels de préoccupation concernant «fenêtres» nécessitant un traitement supplémentaire dû à la déviation d’alignement.
Les exigences spécifiées pour le mur de coupure faible perméabilité ont été atteintes par la mise en œuvre d'un programme d'enquête de l'alignement complet complété par la cartographie tridimensionnelle. Ce document décrit les détails et l'évolution du programme d'assurance de la qualité entrepris au cours de la construction du mur de coupure jet injecté à La Romaine 3.

1.0 INTRODUCTION

Hydro-Quebec is constructing a hydroelectric complex consisting of four generating stations on the Romaine River in the Lower North Shore region of Quebec (Figure 1). This project is the largest infrastructure project in Canada at time of writing. Once constructed, the installed capacity of the complex will be approximately 1,500 MW. The proposed generating station at Romaine 3 comprises a rockfill dam, a flood spillway, a supply main, a power plant with two turbine-alternator sets, and a temporary bypass structure. Construction of the Romaine 3 generating station is scheduled to be completed by 2017; jet grouting was performed at the site in 2014.

Geo-Foundations Contractors Inc. installed jet grouted cut-offs beneath each of the upstream and downstream cofferdams during the summer of 2014. The function of the jet grouting was to provide a hydraulic cut-off between the undersides of both earth-filled cofferdams and the top of rock such that construction of the proposed permanent dam could take place in the dry. An extensive alignment survey program was implemented to precisely verify the orientation of each jet grouted column. This approach to quality assurance was used to modify and supplement the hydraulic cut offs where necessary.

![Figure 1: La Romaine Generating Station -Project Location](image)
2.0 SUBSURFACE CONDITIONS

The subsurface conditions beneath the Romaine 3 earth-filled cofferdams are typical of a river bottom. There is a deep crevice at the center of the channel, where the depth to rock is as great as 33 metres below top of cofferdam (Figure 3). Beyond the crevice, toward the banks of the river, the depth to bedrock is relatively shallow, ranging from 10 to 18m below top of cofferdam. Typical riverbed ground conditions,
consisting of coarse sand, gravel, cobbles and boulders are found on top of the bedrock. Overlying this native material is a 5 to 6 m thick silty-clay engineered fill layer placed to form an impermeable cofferdam. The jet grouted cut-offs were installed to reduce the permeability of the sand and gravel layer. The jet grouted cut-offs were keyed 1.5 m up into the upper engineered fill layer material and 1.5 m down into the bedrock. Boulders, varying from 0.3 m to 3 m in diameter, and cobbles were encountered at various depths within the native soil profile.

3.0 SPECIFIED REQUIREMENTS

Hydro-Quebec prescribed the geometry of the jet grout treatments zone, strength and permeability of the soilcrete. The jet grouting contractor was responsible for the selection of a suitable jet grouting system, spacing of the columns to achieve the desired overlap, drilling method, grout mix design and the jet grouting parameters.

The specified permeability of the jet grouted cut-off was $10^{-6}$ cm/sec, to be proven by laboratory testing of spoil samples. The minimum unconfined compressive strength was specified as 0.6 MPa after 7 days and 1.2 MPa after 28 days. Additionally, the jet grouted columns were specified to overlap by a minimum of 300 mm at every point along adjacent columns. The minimum specified thickness of the cut-off wall was 0.8 m for the single row configuration and 1.5 m for the double row configuration.

A pre-production test program was required to verify the jet grouting parameters and geometric properties of the installed columns. Testing was required at a location approved by Hydro Quebec where conditions were representative (depth, soil type, etc.) of those anticipated at the proposed cut-off wall locations.

The verticality of the jet grout columns was a key requirement of the jet grouting program. The deviation tolerance of the vertical holes was specified as 0.5% of drilled depth. A measurement system approved by Hydro Quebec was required to check the alignment of each drilled hole. When the gap with the vertical exceeded 0.5%, the hole, a supplemental column was to be installed to ensure the minimal overlap was achieved.

4.0 OVERVIEW OF THE JET GROUTING PROCESS

Installation of jet grout columns is typically done from the bottom upwards. A drill string is advanced to the target depth typically with water flush or a weak grout mix to create a drilled hole. The resulting small diameter hole to the bottom of the treated zone sets the stage for jet grouting by creating a passage (upwards through the annular space between the inside of the borehole wall and the outside of the drill string) for evacuation of excess jet grout spoils.

The double fluid process of jet grouting separately supplies grout and compressed air to the bottom of the drill string via separate, concentric passages within the string. Grout is ejected laterally through specially designed nozzles that focus the grout stream for maximum erosive effect. The compressed air meets the grout slurry on the downstream side of the nozzle, shrouding the grout slurry jet (Figure 4) to further amplify its erosive effect.

Jet grouting parameters such as rotation rate, lift rate, injection pressure and the mix design are typically proposed based on the contractors’ previous experience in similar ground conditions, before being tested in representative conditions, evaluated for performance and conformance, and eventually selected for, or modified prior to, production jet grouting.
5.0 PRE-PRODUCTION TEST PROGRAM

A pre-production test program was performed at the Romaine site to establish suitable parameters for production work. Five test columns were installed to bedrock using varying parameters along with modified drilling methodologies to verify the adequacy based on actual subsurface conditions. Three of the test columns were installed using an uncased hole to simulate the proposed methodology for the shallow sections of the cut-off wall. Two holes were installed inside pre-installed sacrificial thin wall slotted PVC pipe to simulate jetting of mixed and loose ground conditions, especially for the deeper holes. Slotted PVC pipes were used to create a conduit for spoils return, especially within the loose sand and gravel layer. The test columns were exhumed 3 days after installation to assess their respective constructed physical attributes, especially the column diameter and continuity of profile. Table 1.0 shows the results obtained from the test program.

The test columns installed in the uncased hole met the 1.2 m diameter minimum requirement. The jet grouting process did not disintegrate the sacrificial PVC casings. A weak cement-bentonite grout was considered in lieu of the sacrificial PVC casings for the deep holes. Laser scanning survey was performed by Hydro-Quebec to establish the nominal column diameter of the exhumed test columns. The lift rate of TC-3 was selected for production work due to the best column consistency and achieving the 1.2 m diameter minimum requirement.
Table 1.0: Results from the pre-production test program

<table>
<thead>
<tr>
<th>Jet Grout Column ID</th>
<th>Drilling Condition</th>
<th>Lift rate, m/min</th>
<th>Specific Energy, MJ/m</th>
<th>Column Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC-1</td>
<td>Uncased hole</td>
<td>0.4</td>
<td>25</td>
<td>1.5</td>
</tr>
<tr>
<td>TC-2</td>
<td>Uncased hole</td>
<td>0.35</td>
<td>29</td>
<td>1.6</td>
</tr>
<tr>
<td>TC-3</td>
<td>Uncased hole</td>
<td>0.45</td>
<td>23</td>
<td>1.4</td>
</tr>
<tr>
<td>TC-4</td>
<td>Cased hole</td>
<td>0.3</td>
<td>33</td>
<td>No column</td>
</tr>
<tr>
<td>TC-5</td>
<td>Cased hole</td>
<td>0.4</td>
<td>25</td>
<td>No column</td>
</tr>
</tbody>
</table>

6.0 JET GROUTING QUALITY CONTROL AND VALIDATION

Quality assurance and quality control were integral to the successful execution of the jet grouting program at this project. The test program, as the principal means of quality assurance, established the parameters necessary to achieve the design geometry, the quality and the strength of the grouted columns. Using this information as a basis for construction, all parameters were recorded during production jet grouting using Geo-Foundations’ proprietary interactive data acquisition and control software installed on the drill rig.

A quality control and quality assurance program based on a combination of field observations, data acquisition (DAQ) system records, field sampling and laboratory analyses which are specific to jet grout column installation was implemented for this project. All measures were taken to satisfy the minimum specified requirements for the cut-offs.

The following quality control checks were performed on grout and spoils samples:

- The specific gravity of the grout and spoils were measured in accordance with the method described in API Recommended Practice 13B-1 with a mud balance.
- The Marsh time of the grout was measured in accordance with the method described in API Recommended Practice 13-1 with a Marsh funnel and a calibrated container.

The following quality assurance measures were implemented:

- Alignment survey of each jet grout column using the SAA Scan.
• Unconfined compressive strength (UCS) testing was performed on spoil samples taken during the installation of the jet grout columns. UCS testing was performed in accordance with ASTM D2938.

• Core sampling was performed to evaluate the consistency of the jet grouted columns and to obtain samples for laboratory permeability testing.

• DAQ records were reviewed daily to verify consistency of the jet grouting parameters versus time within the treatment zone.

The following jet grout installation parameters were recorded for each column by the DAQ system on the drill rig:

• Rotational speed of the drill string
• Lift speed of the jet grout monitor
• Grout slurry pressure and flow
• Air pressure and flow
• Volume of injected grout slurry

An installation report was submitted to the Owner’s Representative for each jet grout column at the end of each jet grouting shift.

7.0 AXIAL ALIGNMENT SURVEYING AND 3-D MAPPING

The deviation of individual jet grouted columns can have significant impact on the performance of structures where continuity is a key requirement. An appropriate drilling methodology combined with a reliable hole alignment survey tool are essential to limit the frequency of occurrences of inadequate jet grout column interlock. Jet grouted holes should be surveyed whenever possible to ensure deviation is within acceptable limits (Kirsh & Bell, 2013). Deviation of jet grout columns is contingent on equipment, accuracy of the rig set-up, treatment procedure, subsoil conditions, drilling orientation and depth. Experimental measurements indicated that a deviation of the axis of the column is unavoidable, even in controlled conditions and should be considered as an inherent defect of jet grouting (Croce et. al, 2014). Deviation can be reduced to tolerable levels by utilizing an accurate deviation monitoring system for each jet grout column.

The alignment of each jet gout hole at the Romaine 3 project was checked using a Shape Accel Array (SAA) measuring system. The SAA, manufactured by Measurand, is a flexible, calibrated hole alignment measuring system designed for repeated use inside boreholes or drill rods. It is a watertight system with robust joints made from hydraulic hose, stainless steel segment tubes, and stainless steel fittings.

Every single jet grouted column had its full alignment surveyed and the information was input to create an evolving set of 3-D images of the constructed work (Figure 5). These images were used on an ongoing basis to adjust the layout of production jet grouted columns as necessary and to guide remedial jet grouting work. The SAA survey data for each jet grout location was transferred into AutoCAD to generate a 3-D profile of the cut-off wall. The profile of the wall was carefully analyzed to identify locations with inadequate column overlap; mapping was done on a daily basis to keep the profile updated. This process also proved useful in planning the jet grout installation sequence.
Supplementary jet grout columns were installed based on the timely review of the 3-D profile by both Geo-Foundations and Hydro-Quebec. The review by Hydro-Quebec was based on 1.2 m diameter cylindrical elements. A typical output from an individual SAA Scan is shown in Figure 6.
8 CONSTRUCTION

8.1 General

The original approach to drilling the jet grout holes involved advancing the drill string to depth in an uncased hole using the rotary mud drilling process, wherein bentonite slurry is circulated through the drilled hole to help evacuate cuttings and to stabilize the borehole wall. A Polycrystalline Diamond Compact (PDC) bit was used to advance the hole through the overburden materials and into bedrock. Upon reaching the desired depth of 1.5m into bedrock and prior to the commencement of jet grouting, an alignment survey was performed and the results of this survey input into the evolving 3-D image of the constructed work.

Jet grouting commenced soon after the verticality of the drilled hole was measured and the SAA probe was retracted from the rods. Grout was batched using a high shear and high speed colloidal mixing plant, with quality control of each batch completed at the automated batch plant before that batch of grout was transferred to the drill rig via a high pressure pump. Upon reaching the drill rig, the grout was delivered to the tip of the drill string through the drill rods and ejected through a set of nozzles located in the monitor at the tip of the drill string. Compressed air was simultaneously ejected around the stream of jet grout to create a buffer zone to allow the jet grout to penetrate into the ground more efficiently and to minimize any influence due to the presence of ground water. The lift rate and rotation of the drill string were controlled via the data acquisition (DAQ) system on the drill rig. All jet grouting parameters were recorded continuously during the jet grouting process.

Soon after commencement of production jet grouting, challenging ground conditions necessitated a change to the drilling approach.

8.2 Shallow section

During the installation of upstream shallow section jet grout columns, it was observed that the deviation of the jet grout column was quite excessive (3 to 10%). The deviation raised concerns regarding the ability to overlap the jet grout columns to form a continuous wall. Furthermore, premature wearing of drill tool was observed which raised concerns regarding the increased production cost. Following a comprehensive review of the monitoring data and information obtained from field observation, the installation methodology was modified in an attempt to increase productivity and to avoid potential windows in the cut-off wall. It was recognized that due to the challenging ground condition, predrilling the borehole using rotary duplex drilling method could help reduce the column deviation. The rotary duplex drill tooling is much stiffer and less prone to deviation during drilling.

8.3 Deep section

Drilling of the jet grout columns within the deep section was initially done in an uncased hole. Boulders and a sloping rock profile resulted in significant deviation and damage to drill tooling. The installation procedure was modified by pre-drilling to help maintain the alignment. A rotary-duplex single rotary drilling system was used to advance a 273 mm OD temporary cased hole 1.5 m in rock and where required for verification purposes 8 m into rock. The drilled hole was backfilled with bentonite slurry
(8%) prior to removal of the temporary casing. Jet grouting was performed into the pre-drilled hole after the hole was backfilled with the bentonite slurry. This process significantly impacted the production rate and the inclined rock face deflected the casing and resulted in large deviation.

The drilling methodology was further modified to limit the hole deviation. Pre-drilling was performed with a casing crown and ring bit using the Robit system, along with a 150 mm OD temporary casing. The Robit system improved the drilling production rates and hole alignment through boulders and the inclined rock face. In addition to the pre-drilling, consolidation grouting was done in the primary jet grout holes where loss of drilling slurry occurred. The consolidation grouting was done under gravity head to stabilize the loose sand, cobbles and gravel layer and to improve confinement during jet grouting. Consolidation grouting was done by tremie grouting inside the temporary casing and retracting the casing in stages to ensure grout coverage.

A detailed drill log was recorded for each hole during the pre-drilling process in order to tailor a suitable approach for pre-treatment and jet grouting. Additionally, a low strength cement-bentonite grout was used to stabilize the pre-drill holes prior to jet grouting. The cement-bentonite grout was allowed to cure for a minimum duration of 24 hours prior to jet grouting. Modifications to the drilling and installation methodologies were based on a timely review of the drilling conditions in conjunction with the data from the SAAScan.

9 DISCUSSIONS & CONCLUSIONS

Interpretation of alignment survey data should only be undertaken with a good understanding of the jet grouting process. Jet grouted elements are not truly cylindrical and consideration of column variability – based on known or suspected subsurface conditions – should be given when evaluating the finished product.

A systematic process of alignment surveying and timely interpretation thereof was implemented at the Romaine 3 project to ensure quality and cost-effectiveness of the jet grouted cut-offs. The data obtained was organized and mapped in a timely manner to identify potential deficiencies and to guide the layout and construction of supplemental columns to remediate those deficiencies.

Despite the inherent challenges associated with constructing overlapping jet grouted elements in difficult drilling conditions, the jet grouted cut offs have performed beyond expectation (Figure 7), as dewatering of the excavation between the upstream and downstream cut offs has been dry to date. Jet grouting was effectively implemented at the Romaine 3 with a clear-cut quality assurance program to create a water-tight cut-off wall.
Figure 7: La Romaine 3, circa 2015, with both cofferdams in full service (source: Hydro-Quebec)

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