ABSTRACT

Three low-permeability cut-off walls were required for seepage control along the upstream toe of two new dams as part of the Lac des Iles (LDI) Water Management Facility Works. The LDI palladium mine is located 135 km North of Thunder Bay, Ontario, Canada. Jet grouting was used to create the low permeability cut-off walls by installing overlapping soil-cement columns. Jet grout columns were constructed using the double-fluid process. A comprehensive quality control program was implemented to ensure that specified geometric properties and performance requirements of the cut-off wall were achieved. An Acoustic Column Inspector (ACI) tool was used to verify the diameters of the pre-production test columns. All jet grout locations were pre-drilled to prevent difficulties resulting from geological conditions and to ensure adequate penetration into bedrock. A three-dimensional profile of each jet grout column installed was generated and updated daily based on the results of pre-drill hole alignment measurements completed at every hole. In-situ permeability testing was also conducted during the pre-production test program and during the installation of the production columns. Permeability testing was performed in-situ and on cast cylinders of soil-cement samples. The low permeability cut-off walls were successfully installed and satisfied the specified performance criteria. Jet grouting was performed between the months of February and May under challenging winter conditions. This paper focuses on the quality management program (QMP) that was implemented to successfully complete this project.

INTRODUCTION

The Lac des Iles Mine (LDI) is located in northern Ontario, Canada, approximately 135 kilometers northwest of Thunder Bay, Ontario. There are three Tailings Management Facilities (TMF) at the LDI site. A new Water Management Facility was proposed as part of the long-term tailings
management plan at the LDI mine. Three low permeability cut-off walls were installed by Geo-
Foundations Contractors as part of the Lac Des Iles Water Management Facility upgrades. The
cut-off walls were required along the upstream toe of the proposed main and saddle dams. In areas
where the depth to rock exceeded 6 metres, jet grouting was used to install the seepage control cut-
off wall; conventional excavation and an earth/rock-filled dam with a geomembrane liner was used
wherever the rock was present within 6 m from surface. The jet grouting scope of work consisted
of 3 no. walls with lengths of 58, 83 and 136 metres. The cut-off wall was keyed into sound
bedrock. The specified criterion with respect to permeability of the cut-off wall was \(10^{-6}\) cm/s and
was to be verified by in-situ testing.

**GEOLOGICAL SETTING**

The surficial geology at the LDI site consists of a blanket of till deposits overlying bedrock. The
till blanket is extensive and bedrock outcrops at less than 10% of the total site area (Hatch, 2015).
Till at this site is typically less than 3 m thick with sections exceeding 6 m in the lee-sides of
bedrock and in valleys between outcrops. Peat deposits with thickness varying from 1.4 to 2.3 m
also cover approximately 50% of the site. The subsurface condition within the footprint of the
work zone consists of organic peat overlying glacial till. The till at this site comprises of sandy silt
to sand and gravel with traces of clay and occasion to numerous cobbles and boulders. A partial
view of the subsurface conditions after the peat layer was removed is shown in Figure 1. In some
localized areas, the till is overlain by discontinuous silt, fill or glacio-fluvial layers. Bedrock is
present within 10 m of the existing ground surface, except for the valley located along the proposed
Saddle Dam, where bedrock was encountered at 14 m below ground surface. Bedrock at this site
is classified as slightly weathered to fresh granite. All jet grout columns were socketed at least 1
m into rock.

![Figure 1. Partial subsurface view within a proposed jet grout segment](image-url)
SPECIFIED REQUIREMENTS

The entire site was subdivided into three segments: Main Dam East, Main Dam West and Saddle Dam; each of these three segments required at least some jet grouting.

The specified cut-off wall stipulated a single row of overlapping jet grout columns. The specified requirements were as follows:

- A minimum jet grouted soil thickness of 1.0 m
- Embedment depth into bedrock ≥ 1.0 m
- In-situ permeability ≤ 10^-6 cm/s
- Unconfined compressive strength (UCS) after 28 days ≥ 1.2 MPa.
- A pre-production test program consisting of a minimum of one sacrificial jet grout column for each segment.
- In-situ permeability proof testing over the full depth of the wall at each segment.

OVERVIEW OF THE JET GROUTING PROCESS

Jet grouting is a ground modification technique used for in situ mixing of soils with a stabilizer (usually cementitious grout). The stabilizer (grout) is injected at high pressures (typically 300-400 bars) through a small diameter nozzle. Grout is injected at high velocity, which enables the jet grouting process to hydrodynamically destroy the natural matrix of the soil and results in a mixing of the stabilizer with the disintegrated soil particles. The result of this energetic mixing is a homogenous and continuous structural soil-cement element (also known as soilcrete) with predetermined characteristics. Jet grouting can be applied to a wide range of soils from non-cohesive, poorly granular soils to cohesive plastic clays.

Jet grout columns at the LDI site were constructed using the double fluid process. Grout slurry and air were conveyed through separate chambers in the drill string (see Figure 2). Upon reaching the intended design depth, jet grouting was initiated with high-velocity air and grout slurry. Grout slurry was used for eroding and mixing the soil. The addition of compressed air shrouded the grout slurry jet, which increased its erosive erosion. This process employed specially built nozzles designed to focus the grout laterally, thus creating the soilcrete column.
PRE-PRODUCTION TEST PROGRAM

The objectives of the pre-production test program were to obtain appropriate jet grout parameters necessary for production jet grouting, to create columns ≥ 1.5 metres diameter, and to demonstrate an in-situ soilcrete permeability of $\leq 10^{-6}$ cm/s. A target column diameter of 1.5 m was selected to provide a minimum wall thickness of 1.0 m, including at column overlap. A total of three pre-production test programs were undertaken - one for each of the three jet grout segments.

The following jet grout parameters were used in the pre-production test programs:

- Grout flow rate = 250 L/min
- Grout pressure = 400 bars
- Lift rate = 0.25 m/min
- Rotation rate = 10 rpm
- Nozzle configuration = 2 no. x 3.5mm diameter

The following jet grout mix design was used:

- W:C ratio (by weight): 1.2
- Cement: Type GU Portland Cement
- Bentonite: Extra High Yield Bentonite (1.5% by weight of water)
- Superplasticizer: BASF - Rheobuild 1000 (0.75% by weight of cement)

**Acoustic column inspector (ACI) and Shape Accel Array (SAA) Measurements**

The column diameter and profile were confirmed by using an Acoustic Column Inspector (ACI) and permeability was determined by in-situ falling head testing. Jet grout spoil (backflow) samples were collected to conduct laboratory testing (UCS and permeability). One of the sacrificial test columns was also exhumed to visually inspect the column diameter over the uppermost 1 m.
The diameter and profile of the pre-production test columns were verified using Keller’s proprietary acoustic column inspector (ACI). The ACI is an acoustic inspection device for checking the diameter of a jet grout column while the subject column is being constructed. Two small diameter holes are drilled at a target distance from the centre of the planned test column and steel feeler rods are installed. Two acoustic sensors are connected on the top of steel rods previously inserted in cement-bentonite backfilled hole (Figure 3). A signal collection system is used to record acoustic data during the jetting process. When jetting the test column, the steel rods and the acoustic collection system detects if the jet stream is penetrating as far away as the steel rods. The signal was displayed on a real-time basis and recorded for post-processing. Interpreting this data can yield the minimum achieved radius of the jet grout column.

A Shape Accel Array (SAA) measuring system was used to check the alignment of each 178 mm diameter pre-drilled hole prior to jet grouting. The SAA, manufactured by Measurand, is a flexible, non-magnetic, calibrated hole alignment measuring system designed for repeated use inside boreholes or drill rods. The SAA is a watertight system with robust joints made from hydraulic hose, stainless steel segment tubes, and stainless-steel fittings. For the LDI project, the SAA string of segments was lowered into the bottom of the pre-drilled hole via the inside of the drill rods. Each segment, 0.5m long x 22 mm diameter, contains sensors to measure acceleration, tilt, and temperature. Special software was used to collect and conduct post-processing of the information to verify the as-built hole alignments and orientations. An evolving set of 3-D profiles was generated for the LDI Project’s overlapping jet grout columns.

The data from the ACI collection system were combined with the geometry taken from the SAA tests to verify minimum column diameters along the entire depth of the test column at every tested location.

Figure 3. ACI sensor mounted atop of steel rod in cement-bentonite backfilled hole

Results from the pre-production test program

The pre-production test columns at the Main Dam West and the Saddle Dam achieved a minimum diameter of 1.6 m based on data acquired from the ACI and SAA. This finding was verified by exhumation of the pre-production jet grout test columns.
At the Main Dam East, drilling of the test column resulted in deviation due to a significant amount of cobbles and boulders that were encountered during drilling. As a result of the ground conditions that were encountered, the spacing between ACI rods and the jet grout test column was not ideal to clearly verify the as-built column diameter. Two additional steps were taken: (1) the test columns were exhumed to verify the diameter; (2) A second ACI test was performed on a production column JG #57.

Figure 4 shows the exhumed overlapping test columns at the main dam east with a minimum observed diameter of 1.6 m. The ACI test on production column JG #57 also showed that a minimum diameter of 1.6 m was achieved.

**Figure 4. Exhumed sacrificial jet test grout columns at the Main Dam East**

**Falling head tests**

Immediately after installation of the jet grout test columns a 75 mm outside-diameter (OD) steel pipe was inserted into the centre of the freshly installed column. A second pipe with an interior diameter of 38 mm (with bottom end capped) was inserted inside the 75 mm OD steel pipe to 2.0 m beyond the tip of the exterior pipe. Wherever this forming process was foiled by one circumstance or another, the permeability testing hole was advanced via diamond coring of the cured jet grout column. In order to form the hole necessary for performing the falling head test, the interior pipe was periodically rotated in the fresh soilcrete prior to initial set. After 3 days of curing time, the interior pipe was retracted, leaving a 2.0 m uncased “formed” hole below the exterior pipe which was left in place to act as a conductor to the permeability test zone.

The falling head test procedure consisted of the following steps:

- The test hole was flooded with water and the water head was brought to the top of the exterior pipe.
• A downhole pressure transducer (Level Troll 700) was lowered into the test hole to continuously record evolving changes in hydrostatic head.
• The Level Troll was extracted and the data were downloaded.
• Hvorslev’s method was used to calculate the permeability.

Falling head test results are summarized in Table 1. All test results confirmed in-situ permeabilities on the order of $10^{-6}$ to $10^{-7}$ cm/s.

<table>
<thead>
<tr>
<th>Location/Segment</th>
<th>Results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dam East</td>
<td>7.2 x 10^{-6} and 3.3 x 10^{-6} cm/s</td>
<td>4 days and 8 days curing time, respectively; formed test hole</td>
</tr>
<tr>
<td>Saddle Dam</td>
<td>8.2 x 10^{-6} cm/s</td>
<td>13 days curing time; formed test hole.</td>
</tr>
</tbody>
</table>

### JET GROUT CUT-OFF WALLS

Installation of jet grout cut-off walls at all three segments employed the same jetting parameters and grout mix design that were verified during pre-production testing.

All production columns were pre-drilled with a separate drill rig prior to jet grouting, on a split spacing sequence so that every interlock was constructed using wet-on-dry jet grouting. Each 178 mm diameter pre-drilled hole was temporarily cased to its full depth and the alignment of each pre-drilled hole was measured with the SAA device. After the hole alignment was measured each pre-drilled hole was backfilled with bentonite slurry and the casing removed. Jet grouting was then performed after lowering the jet grout tooling into the bentonite-filled hole.

Typically, one row of overlapped jet grout columns was constructed along the cut-off wall centre alignment, extending 1.0 m into bedrock. The spacing of columns was 1.1m center-to-center and the minimum constructed diameter was 1.6 m, as confirmed during the pre-production test programmes. Jet grout backflow (spoil) samples were routinely collected at the collar of the jet grout holes for laboratory testing. These samples were provided to the General Contractor for unconfined compressive strength (UCS) and laboratory permeability testing. Compressive strength test results indicated strengths in excess of the minimum specified strength. In total, 251 no. jet grout columns were constructed from March 1 to May 14, 2016, as shown in Table 2.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Total Columns Installed</th>
<th>Drilling Depth (m)</th>
<th>Total Jetting Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dam East</td>
<td>March 1~30, 2016</td>
<td>127</td>
<td>5.3~12.04</td>
<td>644</td>
</tr>
<tr>
<td>Main Dam West</td>
<td>April 1~27, 2016</td>
<td>72</td>
<td>1.9~10.6</td>
<td>392</td>
</tr>
<tr>
<td>Saddle Dam</td>
<td>April 28~May 14, 2016</td>
<td>52</td>
<td>4.6~13.6</td>
<td>434</td>
</tr>
</tbody>
</table>
• **Real-time design adjustments based on QC data**
  The minimum jet grout interlock and wall thickness were achieved throughout the entire wall using a center-to-center jet grout column spacing of 1.1 metres (at the collar) using 1.6 m diameter columns. Wherever the evolving as-built 3-D profiles indicated that the minimum 1.0 m wall thickness was not achieved, supplemental columns were installed.

• **Main dam east**
  One additional column was constructed between columns JG042 and JG043 to fill a section where the jet grout columns were inferred to have deviated. The wall was inferred to be only 0.85 m thick near the bottom of those particular columns. Figure 5 illustrates a 3D view of the as-built jet grout wall at the main dam east based on the data inferred from SAA measurements.

• **Main Dam West**
  One additional column was constructed to repair a potential window resulting from the inferred deviation between columns JG072 and JG073 to fill a section where the jet grout columns were inferred to have deviated at their respective bottoms and the expected wall thickness was only 0.91 m, based on SAA data.

• **Saddle Dam**
  In conformance with the stipulated design all 52 no. columns along the alignment were constructed with each column extending a minimum of 1.0 metre into rock and meeting the minimum specified overlap. The minimum specified wall thickness was achieved as inferred from the combined data resulting from quality control and quality assurance measures.

![Figure 5. As-built overlapping jet grout columns at Main Dam East](image)

**Post-production falling head testing**

As a quality assurance measure, in-situ permeability testing was performed at 3 no. locations along the as-constructed cut-off wall.
At Main Dam East, 2 no. falling head tests were performed in pre-formed holes, using the method mentioned used during the pre-production test program. A third falling head test was performed in a cored hole at JG #64 as follows:

- JG064 was allowed to cure for 2 weeks.
- A 178 mm diameter open hole was drilled to a depth of 4.9 m.
- A 152 mm diameter PVC pipe was installed and the annular space between the borehole and the outside of the PVC pipe was grouted.
- Triple tube (HQ3) coring was performed to a depth extending 4 m beyond the bottom of the PVC pipe.
- A falling head test was performed using the cored section of the hole as the tested medium.

At Main Dam West, one falling head test was carried out using a formed hole and a second test using a cored hole on a production column. The third falling head test was foiled by the presence of large granular materials that were encountered in the soilcrete resulting in the PVC pipe not being able to be advanced into the fresh jet grout column; no results could be obtained.

At the Saddle Dam two falling head tests were performed in the formed holes and one test in a cored hole, as specified. The triple tube (HQ3) coring process was employed for drilling the test hole in one production column at each of the three work segments. The recovered material was delivered to the General Contractor for further inspection and testing. The results of the in-situ falling head proof tests results are listed in Table 3. All results were on the order of $10^{-6} \sim 10^{-7}$ cm/s and thereby satisfied the specified criterion for permeability.

<table>
<thead>
<tr>
<th>Location/Segment</th>
<th>Results</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dam East - JG 090</td>
<td>$9.9 \times 10^{-6}$ cm/s</td>
<td>6 days curing time; formed test hole</td>
</tr>
<tr>
<td>Main Dam East - JG 113</td>
<td>$5.7 \times 10^{-7}$ cm/s</td>
<td>8 days curing time; formed hole</td>
</tr>
<tr>
<td>Main Dam West - JG 48</td>
<td>$7 \times 10^{-7}$ cm/s</td>
<td>22 days curing time; formed test hole</td>
</tr>
<tr>
<td>Main Dam West - JG 71</td>
<td>$1.1 \times 10^{-6}$ cm/s</td>
<td>9 days curing time; cored hole</td>
</tr>
<tr>
<td>Main Dam West</td>
<td>N.A.</td>
<td>Could not install pipes due to a significant amount of cobbles/boulders.</td>
</tr>
<tr>
<td>Saddle Dam - JG 043</td>
<td>$1.2 \times 10^{-6}$ cm/s</td>
<td>10 days curing time; cored hole</td>
</tr>
<tr>
<td>Saddle Dam - JG 017</td>
<td>$4.3 \times 10^{-6}$ cm/s</td>
<td>7 days curing time; formed hole</td>
</tr>
</tbody>
</table>

**QUALITY CONTROL PROGRAM**

The quality control program included the following elements:

- All jet grouting holes were predrilled and the deviation, if any, of each hole, was measured using the SAA to verify its verticality prior to it becoming a jet grout column and to verify, by inference, that the minimum overlap was achieved. Consequently, the jet grout column
locations were adjusted where necessary, or supplemental columns were added. Figure 6 shows a typical borehole deviation plan view from the SAA data.

- Grout and backflow samples were collected daily for laboratory permeability testing and unconfined compressive strength (UCS) testing. All tested samples exceeded the specified requirements for unconfined compressive strength (1.2 MPa). Table 4 provides a summary of the test results.
- Three falling head tests were performed in each segment.
- A data acquisition (DAQ) system was used to record the jet grout parameters, including the pressure, grout flow rate, rotation rate and lift rate.

![Borehole Deviation Plan](image)

**Figure 6. Typical deviation plan view from SAA data**

<table>
<thead>
<tr>
<th>Location</th>
<th>Backflow specific gravity (g/cm³)</th>
<th>Grout specific gravity (g/cm³)</th>
<th>Grout Marsh Time (sec)</th>
<th>Backflow UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dam East</td>
<td>1.70~1.98</td>
<td>1.42~1.48</td>
<td>36~46</td>
<td>3.1 to 3.7 MPa after 7 days</td>
</tr>
<tr>
<td>Main Dam West</td>
<td>1.72~1.92</td>
<td>1.45~1.48</td>
<td>40~46</td>
<td>3.3 to 4.4 MPa after 7 days</td>
</tr>
<tr>
<td>Saddle Dam</td>
<td>1.70~1.87</td>
<td>1.45~1.49</td>
<td>39~46</td>
<td>3.8 to 4.4 MPa after 7 days</td>
</tr>
</tbody>
</table>
LESSONS LEARNED AND CONCLUSIONS

The geological conditions at the LDI site presented numerous challenges for the construction of the jet grout cut-off wall. A comprehensive review of the site conditions and experience gained from similar projects allowed Geo-Foundations Contractors to tailor the execution of the work in order to mitigate delays, address the performance requirements and allow for contingency planning.

There are several key aspects of this project that can be adopted for work required in similar geological settings and weather conditions:

- Alignment readings at all pre-drilled holes were taken without negatively influencing the jet grout production rates and the risk of plugging jet grout nozzles.
- Pre-drilling improved productivity of jet grouting and reduced wear of jet grout drill string and tooling.
- The alignment of each jet grout hole was improved by tailoring the pre-drilling method to suit the subsurface conditions.
- The use of the SAA combined with ACI was a very effective process of verifying minimum column diameter and wall thickness.
- Forming a hole in the fresh jet grout column can be an effective, non-destructive method to check in-situ permeability of production jet grout columns.
- High concentrations of cobbles, boulders, and gravel in the jet grout treatment zone can complicate in-situ permeability testing efforts.
- Hole alignment checks at every hole using the SAA is a very effective method of confirming as-built wall geometry and allows for design adjustments, as necessary, in the field in a timely manner.

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REFERENCES