North American Society for Trenchless Technology (NASTT)
No-Dig Show 2012

Nashville, TN
March 11-15, 2012

Paper F-1-02

Thermal Grouting of BC Hydro's VCCT Project

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ABSTRACT

This paper discusses the efforts and successful completion of the widely watched BC Hydro Vancouver City Central Transmission (VCCT) HDD project. The VCCT project will supply downtown Vancouver, BC with 230kV electricity using power cables placed in underground conduits as overhead power lines were not an acceptable alternative.

The science of thermal grouting of underground electrical conduits has been around for quite some time, but only recently successfully installed in long HDD bores. Thermal grout is installed around underground conduits to remove heat caused by high voltage power transmission. If this heat is not removed, the heat will reduce the amount of power that can be transmitted by these cables. Until recently, the successful thermal grout applications have been installed in cased bores, but in this crossing BC Hydro's construction and engineering required an uncased bore installation. Working with their engineering partners, a reasonable construction and installation system was developed. The thermal grout requirements included:

- Thermal resistivity at or below .80^0 C-m/W at 2% moisture
- Flowable so the grout would fill all the interstitial areas around the conduits, be uniform and isotropic
- Pumpable along the entire length of the bore hole (planned length was 850 +/- meters long)
- Capable of displacing drill mud
- Long set times for installation requirements
- Low heat of hydration
- Low segregation of the grout (i.e., good grout stability)
- Full scale mock-up demonstrating the feasibility of the pumping and drill mud displacement operation
- Down-hole instrumentation in the mock-up and full scale operations

The design process included finding suitable suppliers for the necessary materials. It was important to provide prospective contractors with a buildable approach prior to bidding. Thermal grouting was an engineered solution, not an afterthought. This cooperative team effort resulted in a world class HDD operation.

1. Introduction

BC Hydro's Vancouver City Central Transmission project provides additional electric power for downtown Vancouver. A major portion of this project includes a nearly 850 meter horizontally directionally drilled (HDD) bore that extends from downtown Vancouver and underneath False Creek to Fairview Slopes residential area of Vancouver. This project required working in and around residential and commercial properties, as well within the confines of a large vibrant city.

Beyond the factors of an urban project, was the need for the 1.1 meter (44 inch) bore to be uncased and filled with a low thermal resistivity grout. This alone makes the VCCT project a unique stand-out. Never before has a thermal grouting project of this magnitude been undertaken. Previous attempts (in the United States) at replacing drill mud with a thermal grout in a large bore have been less than successful. From preliminary engineering to final construction, the team of engineers, contractors and consultants explored numerous options to ensure a successful outcome of just portion of construction.

2. Engineering Requirements-Grouting

The engineering team from BC Hydro, working with other team members, decided that an uncased bore was a necessity from a final product delivery point-of-view. In designing this HDD crossing there are several important engineering design considerations which may be categorized broadly into three requirements namely:

1. Thermal Performance requirements
2. Seismic Performance requirements
3. Constructability requirements

The section below addresses the thermal and seismic performance considerations and how that influenced the final HDD construction for this project.

a. Seismic requirements

One of the requirements for this project was that the cable system demonstrate reliable seismic performance from the cables in the duct configuration and meet IEEE 693 seismic criteria. One of the key design methodologies that can affect the cable's seismic performance in an HDD configuration are the proper choice of the entry and exit angles which become quite critical to ensure that once installed the cable system will meet the stipulated seismic performance criteria. This in turn will govern how the HDD bore path will impact construction and the various aspects of this will come to bear from the project constructability. A study of the response of the transmission cables placed within cable ducts along the proposed HDD profile due to seismic forces was conducted. The general methodology and models used for the dynamic analysis of the cables previously developed and adapted by BC Hydro [1-3]. Based on geotechnical field investigation of the soil/rock conditions at the cable alignment, it was understood that the majority of the HDD alignment would likely pass through the weak sandstones present at the stated depths in the False Creek area. Time delay of the seismic excitation input to the various locations along the cable, which is known to affect the calculated forces and displacements, were calculated based on an estimated velocity of propagation through these materials. Earthquake time history records used in the analysis were selected based on a site specific Probabilistic Seismic Hazard Assessment (PSHA). The main objective of the study was to determine if the force and displacement responses to the representative strong motion earthquakes, using the above mentioned methodologies were too high or the displacements too large for the proposed alignment. From this it was deemed that the approach angles of 10° on the North side and 13° on the Southside for the HDD were acceptable.

b. Thermal requirements

Fundamentally, a cable system selected to be placed in the final HDD configurations should reliably carry the rated load current without overheating (i.e., the cable's conductor temperature should never exceed 90°C) for the stated load current and daily load fluctuations. For this project, BC Hydro's planning department defined them to be 1250A and a load factor of 0.9. While the cable's physical features are important to meet this current carrying capability, this choice is greatly influenced by how close or far away are the cables to each other (influenced by HDD pipes; diameter and thickness), the medium they are surrounded with (mud, grout), depth to which they are buried which can all collectively influence the cable's ability to carry the rated current without overheating. The principle design factors that govern the choice of the cable conduit configuration and their impact on cable performance are discussed and they include:

- Diameter and wall thickness of the various HDPE pipes to be used
- The long-term (40-year) thermal stability of the drilling mud/grout and its impact on the cable's long-term steady state ampacity rating. For example, if the cable duct system is surrounded by grout/drilling mud that experiences a monotonic increase in thermal resistivity due to aging, moisture depletion, and in time this can progressively reduce the circuit ampacity ratings.
- The mechanical strength of the ducts system to handle the short circuit forces likely to be experienced in-service.
- The ratio of the cable's outer diameter to the HDD pipe's internal diameter
- The thermal properties of the material surrounding the cables in the HDD pipes
- The number of cables in HDD pipe configuration
- The integrity of the HDD pipe and cable bundle being maintained along the entire route recognizing that the HDD duct spacing has a significant bearing on cable ampacity rating. For example, the closer the cable carrying HDD ducts are to one another the lower the ampacity of the cable for given cable construction and given thermal resistivities of the various layers surrounding the duct system.
- The trade-offs in having a generously spaced duct configuration with a smaller-size conductor cable compared to closely spaced ducts using a cable with a larger-sized conductor cable.
- The considerations of a HDD drill hole with and without a liner and its impact on cable system's thermal performance which has considerable influence of construction.

One of the design challenges confronting the team was the lack of adequate knowledge of the long-term (>40 years) performance of the mud/grout mixtures surrounding the HDD drill hole and its impact on the cable's thermal performance. Due to this shortcoming, it became important to establish the final design thicknesses of the various HDPE ducts (casing pipe, cable ducts, and the fiber optic ducts) by also examining some analytical studies. These dimensions would be dictated by pipe pulling tensions, spacer dimensions, grout injection pressure, duct availability, standard spacer configuration, spacer thickness, and other parameters. Once the Geotechnical consultant established these dimensions the team undertook analyses to confirm that the proposed pipe sizes, thicknesses are suitable for the cable's thermal performance. The team also quickly realized it would require several iterations of HDD design and thermal design to finally establish the HDD reamed hole size and thus expedite their "pilot drill" portion of the work.

A complex finite element model was developed to help with the thermal analyses. The analyses was conducted to develop the optimum HDD configuration required to satisfy all the three important design considerations stated above and thereby ensure good long-term thermal performance of the cable system. Figure1 shows the model used for the analyses at the deepest section of the HDD and Figure 2 shows the iso-thermal contours. Clearly, the analyses show that the cables' temperatures violate the thermal limit of 90 degrees Celsius for the chosen thermal resistivity of the mud/grout. Based on this analyses the requirements for the thermal properties of the mud/grout was arrived at to ensure that the thermal cable limits remained within limits.

To help with long-term thermal monitoring a decision was also made by BC Hydro to procure a power cable with embedded optical fibers that would allow continuous monitoring of the cable's temperature along this entire route while it was carrying the rated current. This information will be used in future to confirm the theoretical analyses and the knowledge gained is expected to help the utility for design optimization in future projects of similar nature.

c. Constructability

Constructability issues are discussed below

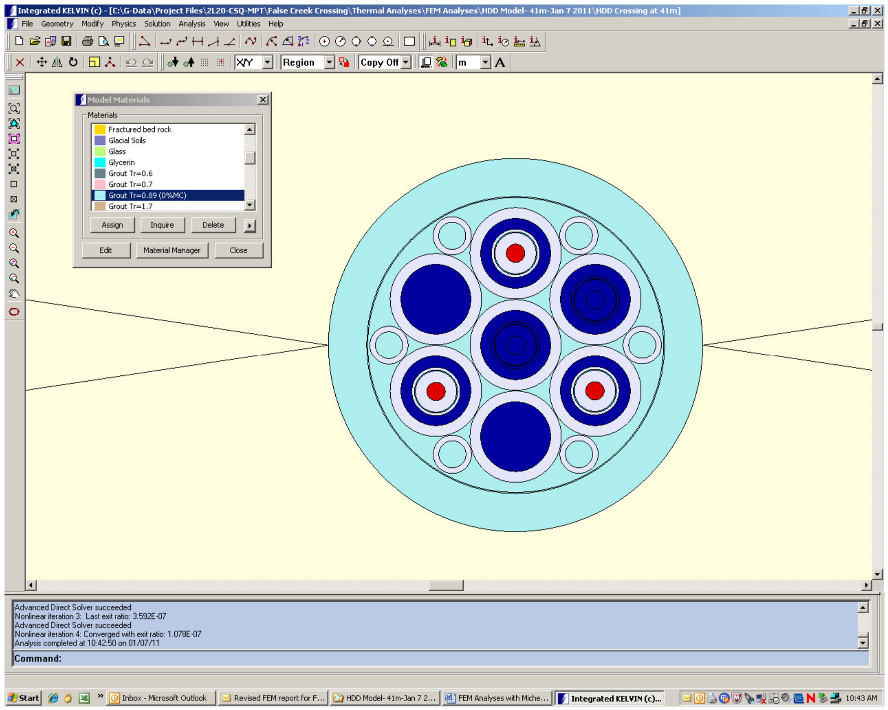


Figure 1: One of the FEM models showing the HDD ducts in grey, grout pipes, power cables and their orientation in the HDD configuration. The pale yellow represents the sandstone in which the bore hall was anticipated.

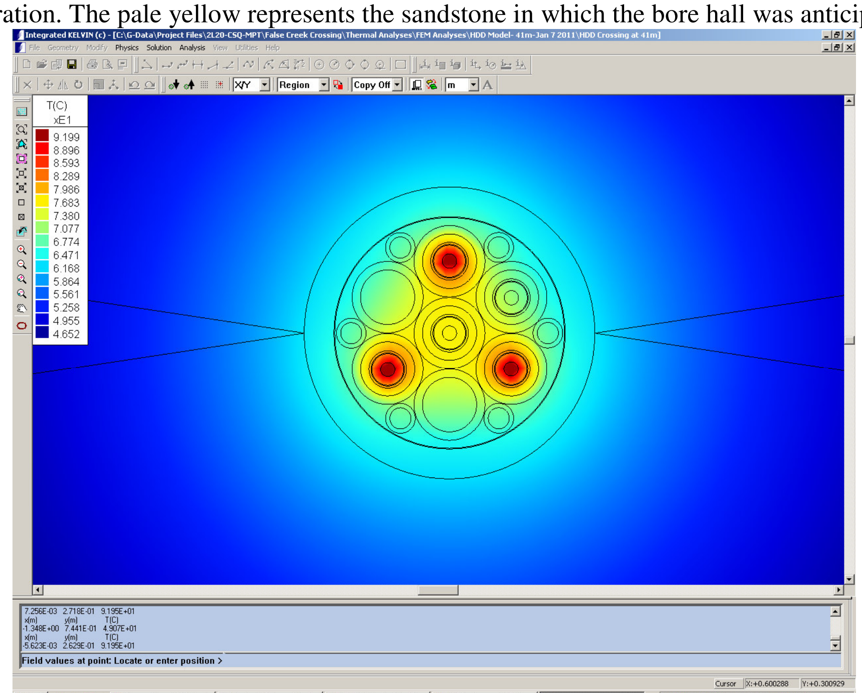


Figure 2: Typical set of iso-therms showing the cable and surrounding temperatures when the cable is carrying 1250A. Clearly the conductor temperature exceeded the thermal limit of 90°C for the chosen grout thermal resistivity is at 0.89°Cm/W (0%MC) was chosen.

3. Grout Trials (Prebid) Mix Design Formulation

Geotherm, Inc. from Ontario Canada was selected as the thermal grout engineer and has been developing grouts and fluidized thermal backfills (FTBs) for upwards of 30 years. He is the scientist behind removing heat from power cables. BC Hydro asked all the team members for input from the construction perspective.

The engineering team (Golder Associates/BC Hydro) required that the grout have the following characteristics:

- Thermal resistivity at or below $.80^0$ C-m/W at 2% moisture (TR less than .80)
- Flowable so the grout would fill all the interstitial areas around the conduits, be uniform and isotropic
- Pumpable along the entire length of the bore hole (planned length was 850 +/- meters long)
- Capable of displacing drill mud
- Long set times for installation requirements
- Low heat of hydration
- Low segregation of the grout (i.e. good grout stability)

The development process started at the Geotherm location in Ontario Canada, rather than at each respective office. This one day meeting provided the basis for the grout mix design. Another criteria was that the materials are locally sourced to the extent possible. Silica materials are best suited for low TRs, cement has a higher TR value, water a very high TR value, and air is has the worst TR value (acts as an insulator). The best initial mix design has a high percentage of silica, some cement, as little water as possible and a near zero air content.
Over 30 mix designs were tried, not only to get the Thermal Resistivity levels at the desired levels, but to improve grout stability, flowability, low heat of hydration and long set times. Sika USA (Lyndhurst NJ) provided two of the necessary ingredients- a super plasticizer with built in retarding function (Viscocrete 2110) and a grout stabilizing admixture (Sika 4R). It is important to solicit the advice of industry experts for their recommendations for these chemicals. It is also very important to test the production cement with the admixtures to ensure the desired results.
Over several weeks, a final proprietary mix design was formulated and laboratory testing was initiated. This work was performed early in the contract specification process so the information could be provided to all the prospective bidders.

Grout mixes must be formulated for each project. There is no 'one mix fits all' design. TR requirements; flow ability and pumpability (two completely separate properties- Griffin 2010); length and volume of bore; availability of materials; ability to manufacture grout; and cost must be taken into account.

4. Specifications

Unusual for contract specifications was a fairly detailed grouting plan. Adrian Hansen, P.Eng. and CGLLC spent many hours laying out the program. It was prescriptive in nature, but still allowed the prospective bidders the flexibility to modify the program. CGLLC suggested inclusion of two very necessary requirements- the need for a full-scale mock-up and borehole instrumentation.

A full scale mock-up is an expense the Owner should want to pay. This exercise is time consuming and expensive, but compared to the multi-million dollar cost of a HDD bore filled with conduit, it was well worth the cost. The mock-up in BC Hydro's case included mixing a production quantity of grout, pumping it through 425 meters of 4 inch HDPE and then displacing drill mud in a 50 meter deep bore. This mock-up represented the most difficult job conditions. Instrumentation included temperature and pressure sensors located at full depth and roughly ¾, ½ and ¼ depth locations. Geokon (New Hampshire, USA) equipment was suggested.

The specifications developed for the prospective bidders included suggested suppliers and an extensive grout plan. This level of detail is rarely seen in specifications, but the degree of difficulty in executing the grouting program demanded this effort

The contract requirements included demonstrating at least a 90% replacement of the drill mud, grout that would have less than 3% dry density change (top to bottom) in a one meter (40 inch) column of grout; TR of $.80^0$ C-m/W at 2% moisture.

5. Contract Bidding and Award

Michels Canada Co. responded to the request for proposal (RFP) on October 14th 2010 and was awarded the project with notice to proceed issued by BC Hydro on December 16th 2010. During the bidding process Michels Canada evaluated the pricing and availability of the Silica flour and potential ready-mix suppliers with the ability to batch and supply the thermal grout for the grouting operations. This was a task of itself as the sheer volume of grout required to perform the grouting as laid out in the RFP documents was going to be both costly and difficult to procure. The main difficulty was the ability to store all of the silica flour in Vancouver prior to the grouting activities taking place. Michels Canada Co. also acquired CGLLC as a subcontractor in our RFP to BC Hydro to assist with the planning and implementation of the thermal grouting of the HDD annulus.

6. From Specifications to Supplier selection- change of materials

After Michels Canada was awarded the contract, the project manager and his team started the required review, selection and purchasing of the grouting materials. Sources of materials and a local ready-mix supplier were identified in the contract documents. However, not previously identified by the ready-mix supplier identified in the Contract Documents were the negative impacts this work would have on his other ready-mix operations and these impacts were reflected in his pricing to Michels at the time of bid.. At this point Michels elected to investigate other avenues to batch the thermal grout and met with Vancouver Ready Mix (VRM), in Langley BC to discuss what Michels Canada needed to perform and could they facilitate our needs. Initially VRM didn't think that they could batch and supply the thermal grout due to logistics of their batching plant in relation to our job site. After some consideration and out of the box thinking by VRM a solution was presented to Michels Canada to build a mobile batch plant closer to the site and have the silica flour delivered in totes instead of bulk which required excess of 400 tones of storage capacity for the silica flour which was the biggest road block to locating a ready-mix supplier that could handle the bulk silica flour. This solution by VRM provided Michels with more control over the batching of the thermal grout.

The supplier for the silica flour as specified in the Contract Documents was changed. Michels Canada requested silica flour samples from 3 silica flour suppliers and performed Thermal Resistivity (TR) testing to see if a more thermal resistant silica flour was available. This proved to be a very positive step as a lower TR silica flour was identified which also provided a cost savings and source that could better meet our project schedule.

7. Retesting

Changing the materials and supplier identified in the Contract Documents required retesting of materials for thermal properties, flow, segregation and heat of hydration. These tests were conducted by Metro Testing Laboratories and Powertech Labs. CGLLC provided input to Metro Testing Laboratories for sample preparation from Baltimore, as the material properties of the components changed from the initial pre-bid testing. After several tests were conducted, a grout was developed, submitted and approved by BC Hydro.

8. Mock-up, Instrumentation

The mock-up exercise provided many perspectives- to the Owner and Engineer the comfort that an extremely difficult process could be completed as planned; from the Contractor's point-of-view that the work could be performed in an efficient and cost-effective manner; from the Consultant's perspective - making sure all parties are comfortable with the program developed to perform the installation of the thermal grout. This process also identifies problems that may arise in the early stages of planning and implementation and allows for adjustments to be made to the overall grouting plan to improve the process and limit the risk to the all parties.

The mock-up grouting trial for the VCCT project included pumping thermal grout through 425 meters (roughly ¼ mile) of 4 inch HDPE pipe and then displace production grade drilling mud from within a drilled hole 50m deep (160 feet +/-). The drilled hole represented the hydrostatic head of the planned full scale bore hole grouting. Michels elected to perform the mock-up in two phases, although not required. The first phase included just pumping the grout through the 425 meters of 4 inch grout pipe, exiting into a spoils pit to confirm the flowability and the selection of the pumping equipment. The 50 meter drilled hole was an expensive operation and would not be risked. Two days after the successful pumping was completed, the process was repeated within the 50 meter hole. The grout pipe was installed at the bottom of the hole as was drilling fluid pump directly off the mud plant at the HDD project site, transported to the test site, and then pumped into the hole completely filling it. Once this was completed batching and pumping of the thermal grout started. Pressure gauges were located at one-quarter points along the 425 meter grout pipe. Michels staged people at each of the pressure gauges to gather real time grout pressures readings during the operation. Temperature and pressure sensors were also installed within in the drill hole and provided down-hole information. See Photograph 1 below.

Pressure readings collected during the trial grouting did not exceed hydrostatic levels. The sensors were adjusted for the specific gravity of the grout, and heat of hydration temperatures, recorded for the 48 hours after the grouting, did not exceed 35^{o}C. This information demonstrated to the Engineers that the grouting process would not damage the HDPE conduits (either from pressure or heat) during the production phase of the grout installation. Geokon vibrating wire equipment was selected- their pressure transducers have internal temperature sensors, providing both readings from one sensor. Their data logger, with software, was reasonably priced and easy to use.

Final mock-up results of the trial grouting showed a 95% replacement of drill mud from within the test hole. This was accomplished by testing slurry density (Specific Gravity) of the grout versus drill mud at the point of discharge.

Photograph 1- Mock-up
Drill mud is displaced from 50 meters below ground by thermal grout. The thermal grout has been pumped 475 meters. The blue wires are leads for the down-hole transducers.

9. Planning for Full Scale Installation

Based on the information gathered during the mock-up, several minor, but necessary changes to the initial grout program were implemented. One improvement was the change from 4 inch HDPE (3.125" ID) grout pipe to a 5 inch HDPE (4.25" ID) for the first phase of production grouting which filled the bore hole at the lowest point of the HDD alignment. This change would reduce pumping pressures and increase grout flow at the critical first stage.
Another change to the Contract Documents included additional secondary grout pipes located at staggered locations only to be used as back up grout lines should an issue arise during the pumping of a specific grout line; quality control (QA,QC) at various locations (temporary batching area and the two pumping locations); greater protection for the instrumentation wiring during HDD pullback; and a full one day delay between Phase One and Phase Two of

the grouting plan to allow the grout to harden prior to secondary stage pumping. Successfully executing a grouting operation of this magnitude requires planning and then holding to that plan. (Ref 7)

10. In-field Quality Control

In-the-field quality control required technicians at various locations performing similar tasks. The required testing included slurry density (specific gravity); air content and thermal resistivity (TR). The thermal resistivity testing is essentially after the fact as final TR values occur when the grout has hardened. The specific gravity indicates the water to solids ratio is within specifications and is the truest pre-indicator that the grout will meet the TR values. Air content, by specification, was 3% or lower. All field tests of air content were 0.7% or lower, with typical values at 0.5% or less. Less air means better (lower) TR values for any given mix design. Higher specific gravity for a given mix design also means lower TR values for a given mix design.

The lowest specific gravity limit for the VCCT grout was 2060 kg/m^3 or roughly 128.6 lb/cf. Targeted value was 2080 kg/m^3 or 129.9 lb/cf. This grout was as heavy as concrete. With grouts of this nature, the physical behavior is susceptible to minor variations of water content. Too little water and the grout will not flow and be difficult to pump, too much water and the TR values increase (lower is better) and is more likely to segregate or separate.
The grout plant was located about 30 minutes away from the project site(s). This necessitated the quality control checks at two locations. The first check, at the plant, ensured that the grout met all the initial parameters; the second check validated any changes made by the grouting superintendent at the pumping location. This double check allowed for adjustments to be made due to waiting times or minor interruptions of delivery due to the heavy Vancouver traffic and with secondary test results available, admixture and water levels could be adjusted on site to ensure the grout was ready to go prior to pumping. This was permitted by specification due to the very sensitive nature of the grout.

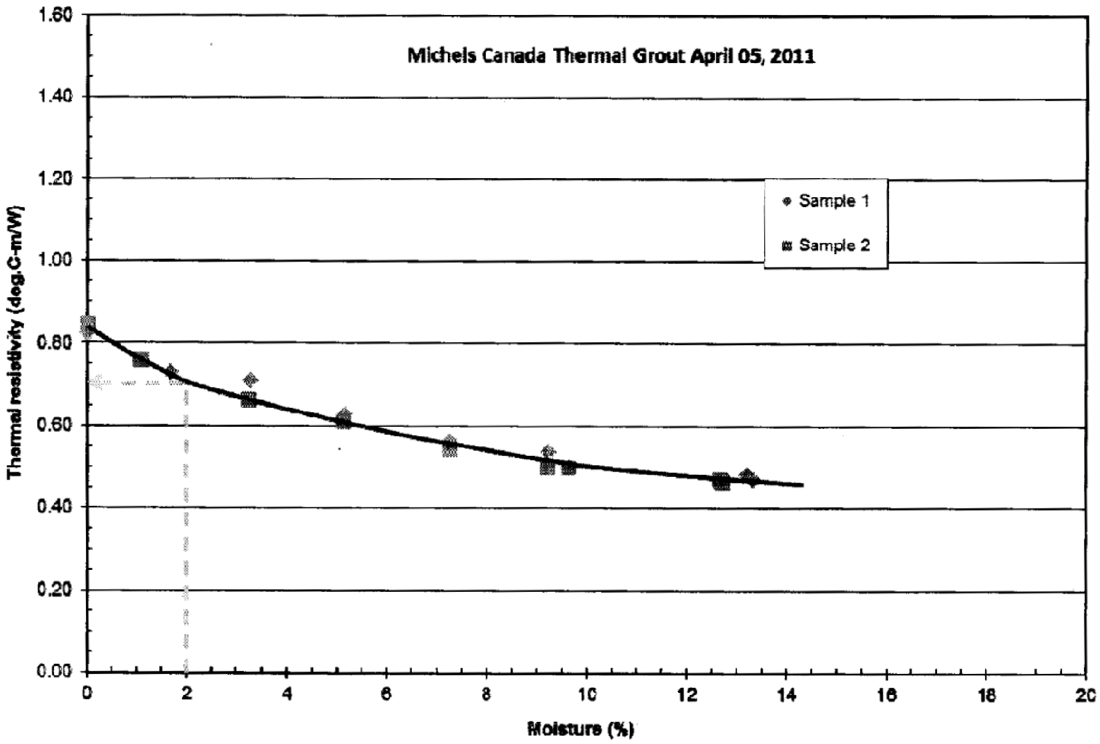
A requirement of 90% drill mud replacement from within the bore hole was needed to be confirmed for the grouting to be deemed successful. It was difficult to test spoils specific gravity with collected and usable samples. Calculated grout volumes and theoretical bore dimensions proved nearly 92% replacement of drilling fluid from within the HDD bore hole. Field testing of TR values showed an overall average TR of .75, significantly better than originally specified.

11. Full Scale Instrumentation

Geokon vibrating wire technology were installed and utilized for this project both in the mock-up and in production grouting. Selection was based on ruggedness, price and availability. The sensors were shipped wired full length with the longest cable nearly 2500 feet. In the mock-up, pressure/temperature sensors were located at the bottom of the hole and roughly ¼ lengths thereafter. In production bore, sensors were located at approximately 1/6th increments along the projected bore. Sensors were strapped to the conduit bundle and protected with rock shield as they entered the Laurel Street opening (Exit side of the bore). The two datalogger were installed and located at this location for the duration of the grouting operation.

12. Full Scale Delivery and Operations

Grouting Operations took place in Downtown Vancouver (Entry Side for the HDD) and in the residential section of Fairview Slopes (Exit Side for the HDD). Both areas presented operational roadblocks. The ready mix trucks had to navigate through downtown rush hour traffic to deliver the grout. This resulted in delivery times from the mixing times to the site upwards of one hour. There was sufficient parking and laydown area for the work. BC Hydro did a remarkable job of public relations to keep everyone informed as to work times, traffic disruption, noise, and impacts to the public. Truck loads were held to roughly 7.4 cubic meters of grout. Any more would have resulted in grout splashing from the rear of the trucks due to hills and bumps along the delivery route.



Thermal Resistivity Test Results

Photograph 2
From Downtown David Lam Park looking across False Creek to Fairview Slopes

Grout was mixed in a warehouse district not far from Vancouver International Airport by Vancouver Ready Mix. This area is about 10 km (7 miles) from the work area, but anywhere from 30 to 60 minutes to the site depending on traffic. The warehouse area had to store 1200 metric tons of dry material; have room for ready mix trucks to enter and turn around and a water tank for mix water. The trucks were loaded with water and admixtures by a calibrated delivery system provided by Sika Corporation (Lyndhurst NJ USA). Thereafter, dry materials were added using a DSS (Oxnard, CA, USA) auger system, using the prebagged materials. Although not as fast as a ready mix plant with silos, accurate delivery of the dry components was controlled using the supersacks. After mixing all components, specific gravity and air content tests were conducted on every batch of grout prior to leaving the plant. This allowed for adjusting admixture levels, water content, and in two instances out of nearly 80 batches, the addition of one additional bag of dry material due to initial miscount. This assured the grout team on site that their grout met specifications.

On Day One of grouting, nearly 160 cubic meters of grout was pumped. On Days 3, 4, and 5: 89, 107, and 71 cubic meters were pumped, respectively. Grouting should be uneventful, as was the case in Vancouver.

Photograph 3
Grouting in Downtown Vancouver

13. Summary

The grouting of the Vancouver City Central Transmission HDD bore was a critical part of the overall project. Proper engineering, planning before construction and execution of the established procedures during the construction made the grouting a tremendous success. The magnitude of the overall project, and the impact for the City of Vancouver, places this construction as one of the most sophisticated underground jobs of 2011. Grouting needs to be included in the engineering and planning stages of any underground construction project and not left as an afterthought.

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