Cutoff Walls for Diamond Mining in the Arctic

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1. Origin of Diamonds

Diamond-bearing kimberlite originates at a depth of about 150 km below the earth’s surface. There, the diamonds had been formed in the magma about 1 billion years ago under approximately 5000 MPa pressure and temperatures of more than 1000 degrees Celsius. Volcanic activity, around 55 million years ago, causes molten rock to rise with a speed of between 10 and 30 km per hour through deep fissures in the earth’s crust until it erupts to form a volcano. There it cools and forms kimberlite pipes, volcanic chimneys in the parent rock, filled with kimberlite ore. In northern Canada the parent rock is frequently granite, a very hard material.

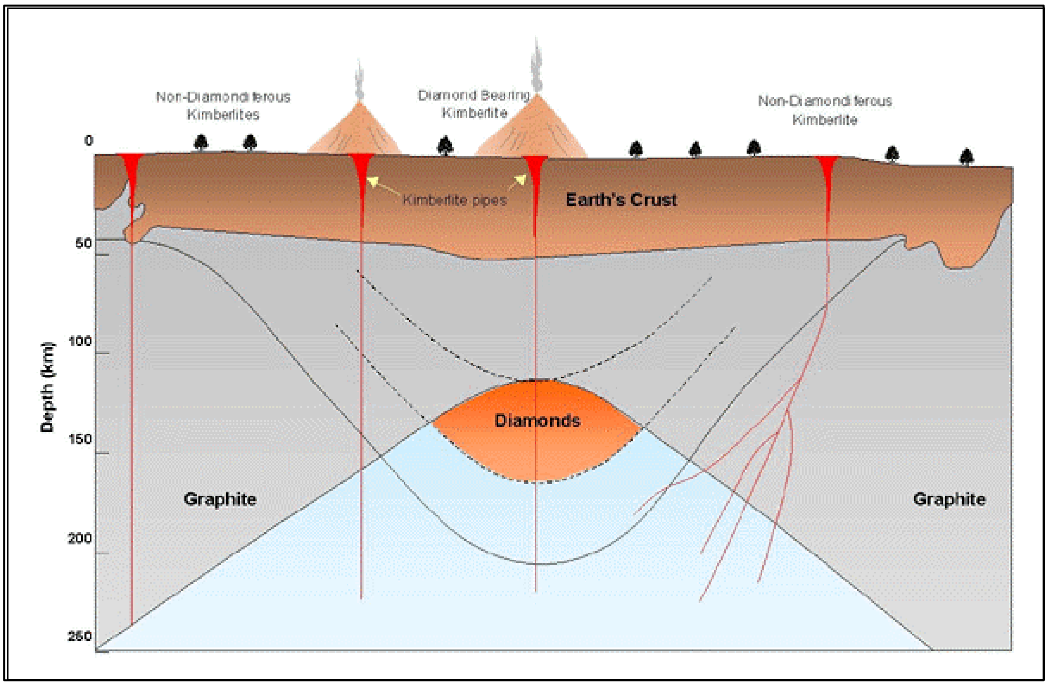

Fig.1: Origin of Diamonds

Initially the volcanic deposit is formed in the shape of a cone, however glacial action typically erodes the upper shoulders of the cone, and that eroded material is transported “down ice”, sometimes thousands of kilometers. Since kimberlite is a relatively soft rock, the erosional process liberates diamonds from their host ore.

Therefore diamonds are recovered from two sources:

1. The volcanic kimberlite pipes themselves – such as in the kimberlite mines of central Africa, Russia and Canada.
2. Alluvial diamonds that have collected in old river beds, on ocean beaches or in the sea itself. Alluvial diamonds occur predominantly in southern Africa and in India.

Rough diamonds are ideally clear, flawless and have an octahedral form. The majority, however, contain impurities that impart a color, many have flaws and many are irregularly shaped. Rough diamond values therefore range between $1US to over $1000US per carat. (1 carat = 0.2 grams)

Fig. 2: Rough diamonds

2. Diamond Exploration in Canada

Prospectors have searched for diamonds in the Northwest Territories of Canada since the 1970's. After years of failure and uneconomic discoveries in northern Canada, Diamet succeeded in 1991, discovering kimberlite pipes in the area near Lac de Gras. The initial discovery sparked a flurry of diamond exploration activity in the Northwest Territories, with many small exploration companies and large global mining corporations like Rio Tinto, BHP and DeBeers participating. To this day, a large fraction of worldwide diamond exploration budgets is being expended on the search for diamonds in Canada.
The Diamet / BHP kimberlite discoveries proved to be very rich, and led to the construction of the first diamond mine in Canada, the Ekati mine, which began production of diamonds in October, 1998.

The second Canadian diamond producer is the Diavik mine, a joint venture between Rio Tinto of London, and Aber Diamond Corporation of Toronto. The Diavik mine began production of diamonds in December, 2002.

3. Diavik Project Summary

The Diavik project site is on a large island in Lac de Gras, located about 35 km southwest of the Ekati mine, and 300 kilometers northeast of Yellowknife, the capital of the Northwest Territories. The kimberlite pipes lie within Lac de Gras, fairly close to shore, in water of 15 to 30 meters depth. In all, 4 kimberlite pipes have been determined to be economic, and the first phase of the project involves bringing into production the first two pipes: A154 North and A154 South.

All of the kimberlite pipes are planned to be mined initially using open pit techniques. In order to enable this, encircling dikes are built that are subsequently made water-tight by installation of a plastic concrete cut-off wall. Connection to the bedrock surface is accomplished by jet grouting the contact zone and fractures in the upper granite bedrock are sealed by pressure grouting. When the dike is built, and the water seepage cutoff components are completed, the pool that has been created is pumped out. After dewatering, an average of 6 meters of glacial soil deposits are removed from the planned mining area.

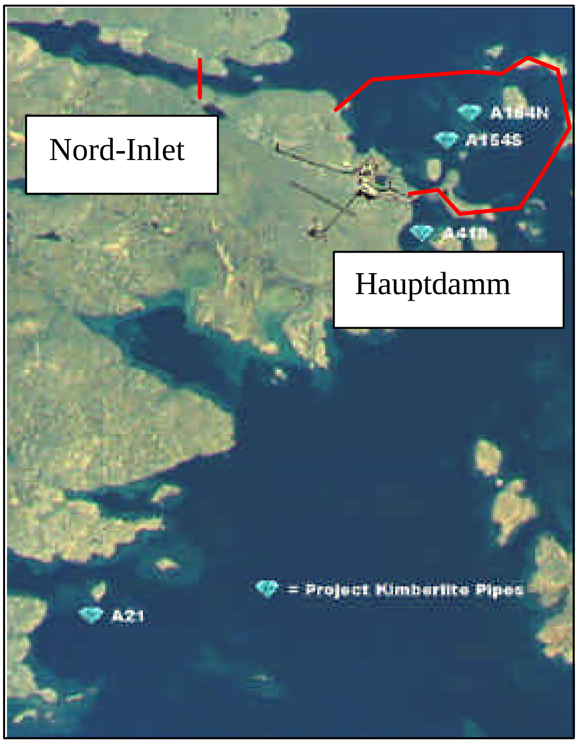

Fig. 3: Location of the kimberlite pipes and dike centerline.

Due to the northern location of the construction site, being only 200 km south of the Arctic Circle, the construction season for dike building, and especially for excavation of the cut-off walls, is limited to the period from the middle of May to the middle of October each year. Outside of this period, temperatures can drop as low as –54 degrees centigrade, and work during the long winter season is not possible. The construction season could be extended into the month of

November, until temperatures drop to about –28 C, if careful equipment protection measures are adopted and if the high pressure grouting and jet grouting mix / pump stations are enclosed and heated.

The construction site is only accessible by road for a period of about 10 weeks, beginning in February, when an annual ice road is constructed from Yellowknife. Thorough planning and attention to logistics are essential for the entire summer construction effort. Any parts or materials that are overlooked when the winter road is closed, must be flown to site from either Yellowknife or Edmonton, Alberta.

Scheduling for the entire dike construction consisted of:

- Mobilization of equipment and materials on the ice road: February – March, 2001.
- Construction phase I: May – October, 2001.
- Mobilization of equipment and materials on the ice road: February – March, 2002.
- Construction phase II: May – August 2002.
- Dewatering of the dike pool: August – October, 2002.
- Excavation of till from A154N and A154S pit area: October – December, 2002
- Beginning of mining and diamond production: December, 2002.
- Demobilization over the winter road: February – March, 2003.

The dike construction scope can be summarized as follows:

Length of the dike centerline:	3,809 meters
Volume of dike materials	3,000,000 cubic meters
Vibro-densification:	290,000 cubic meters
Diaphragm wall:	33,000 square meters
Jet grout wall:	18,000 square meters
Dewatering:	10,300,000 cubic meters
Seepage rate:	800 liters / minute total average

The total construction cost, including all the facilities built to support mining operations and recovery of diamonds, amounted to $1.3 billion Canadian. Average kimberlite processing is planned to be at a rate of 1.5 million tonnes per year, with an average grade of 4 carats per tonne. The average value is estimated to be about $62US per carat.

4. Technical Considerations of the Diavik Project

4.1 A154 Dike Construction

No natural, suitable materials were available on the island, so all the dike construction materials had to be produced from quarried rock. A granite quarry was established that fed up to 28,000 tonnes per day of blasted rock to a mobile crushing and screening plant. Primary and secondary crushers, a wash plant and multiple screen decks were used to produce the necessary gradations of crushed rock. The products used were as follows:

A1 – Fine crushed rock with a maximum grain size of 54 mm, used as a filter zone under the downstream side of the dike. This material was also used to construct a 10 meter wide dike core, through which the cut-off wall was constructed.

A2 – Coarse crushed rock with a maximum grain size of 200 mm, used for the downstream flank of the dike.

A3 – Very coarse quarried rock with a maximum grain size of 900 mm, used for the upstream flank of the dike.

Construction of the dike itself consisted of 3 principal steps:

1. Removal of fine lakebed sediments by means of a cutter-suction dredge.
2. Underwater placement of a filter blanket by means of a barge-mounted crane and skip bucket.
3. Placement of the A1, A2 and A3 materials simultaneously, to form a zoned embankment.

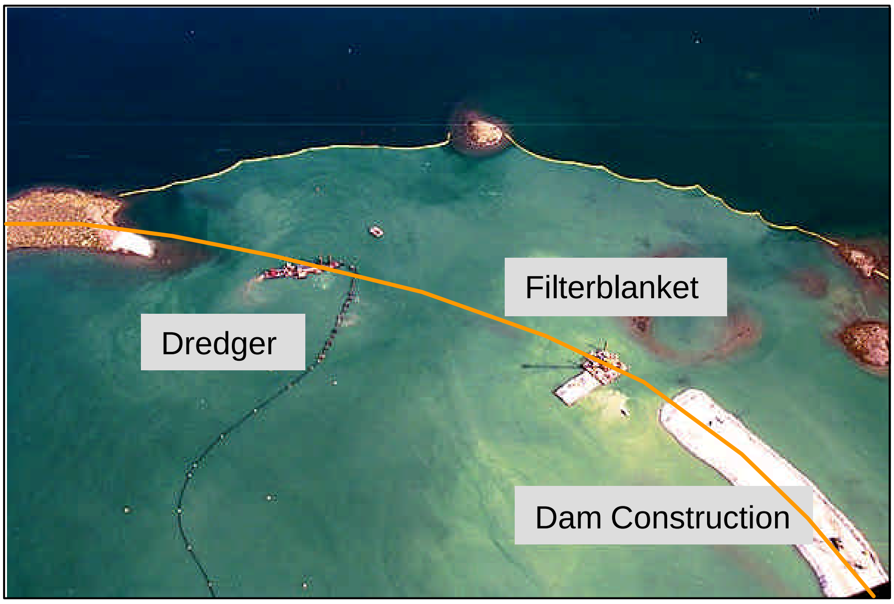

Fig. 4: Dike Construction

4.2 Dike Core Compaction

The central core of the dike was compacted by vibro-densification, using TR75 deep vibrators, carried by a BS 6100 track-mounted crane with integrated hydraulics.
An area extending 5 meters on either side of the panel wall centerline was densified, from the surface down to the contact between the A1 material and the natural lakebed. The maximum depth of vibro-densification was 27 meters.

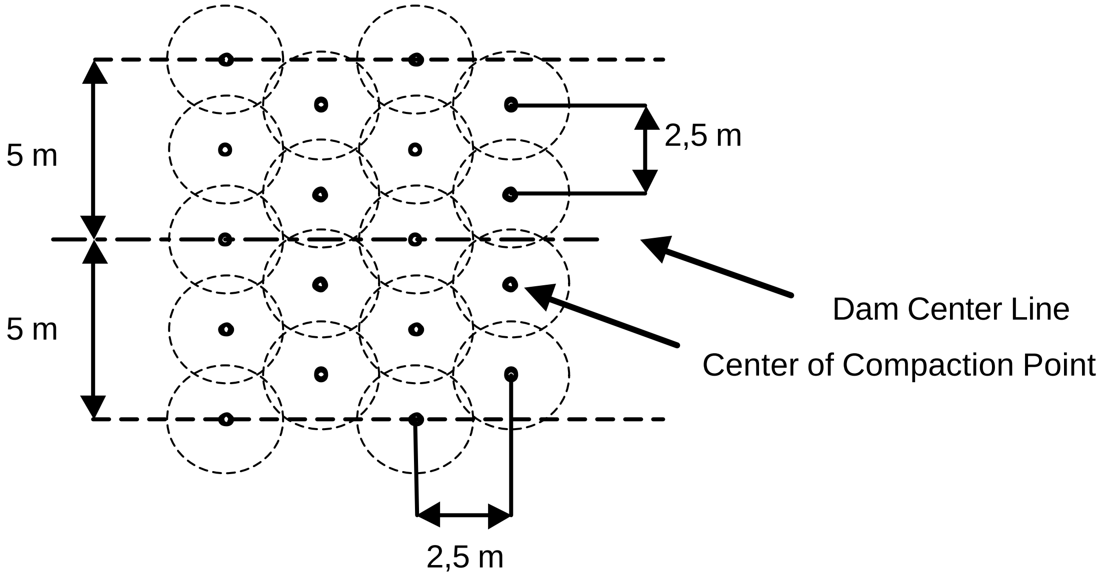

Fig. 5: Dike core compaction layout.

Fig. 6: Compaction with TR75 deep vibrators

With this deep compaction, the internal deformation resistance of the dike is increased, settlement potential is decreased, and a dense core material is created that will support construction of the cut-off wall. Becker hammer testing, that was conducted before and after vibro-densification of the zone A1 material, established that a very good compaction effect was achieved. Blow counts of about 5 were recorded in the A1 before compaction, while typical values of 20 or more were recorded afterwards. The crushed granite rock material was found to be very abrasive, however, and vibro-densification caused considerable wear at the vibrator tip. Continuous production was assured by the use of a second vibrator, so that one could be used while the other one was being resurfaced. In total, about 290,000 cubic meters of A1 material were compacted.

4.3 Diaphragm Wall Construction

4.3.1 Guide Wall System

Precast reinforced concrete guide walls were fabricated locally on site, allowed to cure and then placed in parallel pairs in preparation for excavation of the diaphragm walls. Non-woven geotextile fabric was used to cover the joints between adjacent panels to prevent loss of the bentonite slurry used to keep the cut-off wall trench sides from collapsing.

Fig. 7: Precast concrete guide wall.

4.3.2 Excavation Conditions and Equipment

Excavation for the diaphragm wall construction encountered 5 different ground conditions:

1. A1 crushed rock
2. Till
3. Frozen till
4. Boulders
5. Weathered granite

- A1 Crushed rock.

Due to the careful quality control of gradation during crushing and screening, and the vibro-densification after placement, this material was very stable during excavation. Cut-off wall trench sides did not overbreak, except to an occasional minor extent. In the spring of 2002, some frozen A1 material was encountered, but excavation advanced without difficulty, using heavy hydraulic grabs.

- Till

Glacial deposits at the site were typically very heterogeneous. Especially in shallow water near shorelines, boulder fields up to 3 meters thick were often encountered. In other areas, sandy zones were found, of varying consistency. Large overbreaks occurred during excavation of the till, using hydraulic grabs and hydraulic cutter, which can be attributed to two causes:

1. The boulder fields were washed free of their fines components, by wave action and dredging before dike construction. These boulder zones became unstable during trench excavation.
2. Shocks caused by equipment action during trench excavation then led to local liquefaction of the till, resulting in sloughing of soil into the trench excavation.

When these phenomena were encountered, the diaphragm was not able to be installed down to the bedrock surface, as planned.

- Frozen Till

The project site lies within the continuous permafrost zone of Canada, and permanently frozen ground occurs on all islands within Lac de Gras, near shorelines where the water depth is less than 2 meters, and on the mainland. The ground surface only thaws to a maximum depth of 3 meters in the summer. The composition of this material is the same as unfrozen till, except that some ice also exists in the material. Boulders that are a frozen part of this till are very difficult to break using heavy chisels, because they are frozen elastically in the ice/soil matrix. Due to the slow rate of excavation progress, the warm bentonite slurry in the excavation, which is at 5 to 10 C, thaws the sides of the excavation. The slurry cannot penetrate into the frozen ground, so no filter cake forms on the trench walls, and freshly-thawed parts of the till fall into the trench. The original plan to excavate frozen till using hydraulic grabs, was quickly changed and the BC 40 Trench Cutter was substituted. The cutter was equipped with roller bits wheels, which worked satisfactorily from the outset. Boulders embedded in the till could be cut quickly enough to allow the cutter to reach the desired trench depth. This procedure still resulted in melting of the permafrost due to the thawing action of the warm bentonite slurry, and a progressive overbreak resulted. Thus excavating a trench in permafrost became a time dependant process.

Fig. 8: Removing granite boulders from frozen till by Hard Rock Roller Cutter

- Boulders

Typical boulders consisted of hard granite, with an unconfined compression strength averaging 115 MPa. Boulders measuring up to 1 meter on a side were excavated with the hydraulic grabs, while larger boulders were cut by the trench cutter BC 40.

- Weathered bedrock

The diaphragm wall had to be connected to bedrock, to ensure the performance of the cutoff. Weathered bedrock was reliably cut using the cutter with hard rock roller bits.

Because further mobilization of equipment during the construction season was only possible by air, provision had to be made for an adequate selection of equipment to deal with unexpected ground conditions. To be able to produce approximately 35,000 square meters of cut-off wall in only 7 months, with imprecise geotechnical data describing the site, the following combination of equipment was selected:

- 1 BC 40 Trench Cutter, 800 x 3200 mm, with hard rock roller bits.
- 3 GB 60 hydraulic panel excavation grabs with 800 x 3200 mm buckets.
- 1 GB 60 chassis equipped for chisel handling, with round and box chisels.
- 2 BE 500 desanding units, with all necessary equipment for bentonite slurry formulation and processing.

Special attention was paid to the requirements of the hydraulic grab units. 18 tonne hydraulic grabs were chosen, and the GB 60 base carrier was selected to handle the heavy buckets. Optimal performance in the toughest excavation conditions was obtained by using an hydraulic grab in combination with the chisel unit, and a 30 tonne capacity winch was fitted to the chisel to prepare for rugged conditions.

4.3.3 Diaphragm wall construction

A total of 32,700 square meters of 80 cm thick diaphragm wall were built for the dike cut-off, using a two-phase procedure. Diaphragm wall support during the excavation was provided by means of a bentonite slurry, which was subsequently displaced by tremieing a plastic concrete mixture into the trench.

Fig. 9: Cutter and grab used in panel wall construction

When design of the plastic concrete mix was being determined, the following factors had to be taken into consideration:

- Only crushed aggregates are available on site
- There is only a limited supply of natural sand in the local area.
- Cement and bentonite must be transported over long distances to the construction site, making those materials very expensive.
- The water supply is from Lac de Gras, where the temperature was +3 C, thus requiring heating of the water before use.
- Concrete installation by the use of tremie pipes
- Plastic concrete delivery trucks would occasionally be exposed to temperatures down to –20 C.
- Typical curing conditions in-situ, will be at a temperature of only +3 C.

- In permafrost areas, curing concrete will be exposed to ground temperatures of –10 C.
- The plastic concrete must withstand deformation of the dike during dewatering of the pool.
- The plastic concrete must withstand shock created by production blasting in the mine.
- Long term behaviour.
- Freeze / thaw behaviour in the upper permafrost zone

After 3 years of work in concrete laboratories in Canada, a mix design was determined that addresses all of these factors satisfactorily. The design was finalized through close collaboration between the Diavik engineering team, the engineering consultant, SNC-Lavalin out of Montreal, the testing laboratory of EBA in Edmonton, and the technical support department of Bauer.

The plastic concrete mix design that was used, produced a 28 day compressive strength of 2 MPa and consisted of the following proportion of components:

1.	cement	58 kg
2.	bentonite	40 kg
3.	water	412 kg
4.	fine aggregate, 0-8 mm	668 kg
5.	coarse aggregate, 8-16 mm	668 kg

4.4 Jet Grout Injection

4.4.1 Equipment

Since the jet grout installation could not be done until the plastic concrete had cured sufficiently, and since the jet grouting was the last step in the construction of the cutoff system, this activity was always on the critical path of the construction schedule.

The requirements of the jet grout equipment specifications were as follows:
- Column verticality <0.5%
- Drilling procedure that would not destroy soft plastic concrete, while being capable of penetrating till with large boulders, as well as granite bedrock.
- Highest productivity and availability.
- Suitable mobile equipment for working on the 3.8 km long dike.
- Working temperature as low as –20 C, and as low as –54 C when in winter storage.
- Handling of cement and bentonite in 2 tonne “Big Bags”.
- All components shipped in containers suitable for ocean and land transportation.

Based on these requirements, Mischanlagentechnik (MAT), a sister company of Bauer Maschinen GmbH, developed and optimized the following for use on the project:

- Big Bag task stations with heated horizontal silos.
- Water heating station that used water from the lake and heated it 6 degrees C.
- Fully automatic mixing station for both 2 and 3 phase jet grout injection.
- High pressure jet grout injection pump built into a heated container.
- UBW 09, a compact drill rig with drill rod magazine, that could handle rods 4 meters long and 152 mm in diameter.
- BG 22, a jet grout injection unit, with a lattice mast capable of working in arctic conditions at depths up to 27 meters

4.4.2. Jet Grouting at the North Inlet Dike

Construction of a dike across the mouth of the North Inlet created a pond that was used as a settling basin for the silty water that was pumped out of the pool created by the A154 dike. After several design changes during the construction phase, the dike was constructed with a cut-off that was only 1 meter higher than the original lake surface. The dike was sealed with overlapping jet grout columns.

Fig.10: Jet grout injection at the North Inlet dike

A row of jet grout test columns was constructed to determine the diameter created in typical A1 crushed rock, as well as in frozen till. It was demonstrated that columns greater than 2 meters in diameter were produced in the A1 material, and 0.8 meters diameter in frozen till.
Consequently the column spacing to create a continuous cut-off was chosen to be 0.75 meters in unfrozen till and A1 material and 0.6 meters in frozen till.

Fig.11: Excavation of test columns in frozen till

The following jet grout injection parameters were finally selected:

1. System: two phase, with compressed air and high pressure grout
2. Column spacing: 0.6 / 0.75 cm on the cutoff wall centerline.
3. Nozzle diameter: 4 mm
4. grout pressure: 400 bar
5. Jet grout mix:
    a. 464 kg of cement
    b. 30 kg of bentonite
    c. 1000 kg of water

The same jet grout injection parameters were later used in the construction of the A154 main dike. Altogether 2950 lineal meters of jet grout columns were produced at the north inlet dike. The cutoff wall integrity was proven by pumping water out of the North Inlet pool. The level was lowered by 4.5 meters and minimal seepage through the dike was observed.

4.4.3 Jet Grout Injection at the A154 Dike

The original design for the diaphragm wall required that it be installed down to the top of bedrock. Jet grouting was planned to begin 1.5 meters into the bedrock, and extend upward 0.5 meters into the previously-constructed diaphragm wall. With that design, weathering of the upper bedrock, as well as imperfections at the bottom of the plastic concrete wall would be addressed, and the diaphragm wall together with the jet grouting would provide a continuous cut-off.

When the previously-described instability of the trenches during diaphragm wall excavation in deep till was experienced, it became practically impossible to excavate all the way to bedrock for the panel construction. Therefore, in a number of areas along the 3800 meters of dike centerline, the diaphragm wall construction was terminated at a higher elevation. In those situations, the height of the jet grout column connecting bedrock to the diaphragm wall was raised, thus making longer jet grout columns.

A critical requirement, especially when drilling jet grout holes through till, was to achieve the required verticality tolerance of 0.5% in all directions, thus ensuring adequate overlap of adjacent single columns. Also, it was vital to complete the 152 mm diameter jet grout drilling through the recently-completed panel wall sections, without breaking through either side of the panels. The UBW 09 drill rig with rod magazine achieved these drilling accuracies satisfactorily. Each completed borehole was surveyed for deviation, and it was confirmed that about 98% of all holes met the required specification.

Fig. 12: UBW 09 drilling jet grout injection holes

The BG 22 jet grout injection unit with lattice mast extension allowed the production of jet grout columns up to 27 meters high, without disconnecting the drill rods. In very deep locations, the drill rods string was extended to 33 meters maximum.

Fig. 13: Jet grout mixing and pumping station, with BG 22 in the background.

To be prepared for all eventualities on the remote construction site, 108 mm triple tube drill rods were mobilized, however these were only used in two phase jet grout injection. If conditions had warranted, three phase operation was possible using these rods.

5. Quality Control and Production Data Recording

The construction schedule was extremely weather dependant, and delays in completing the cutoff would jeopardize the overall project completion date. Also, mining of the open pit to 200 meter depths inside the dike depended on the integrity of the cutoff. For these two reasons, a complete record of all production and equipment operating data was required. On a daily basis the data had to be collected, analysed and submitted to the customer. Due to the high production achieved by 8 rigs, working on a 24 hour per day basis, 7 days per week, for the cut-off wall construction, jet grout injection and vibro-densification, data recording could only be done electronically.

All production and equipment operating readings (about 20 parameters per rig) were recorded each second, and temporarily stored electronically at each rig. At the end of each working shift, the accumulated data were transmitted by radio to the site office, reviewed and archived. The analyzed results were delivered to the customer every day, both electronically and in paper form.

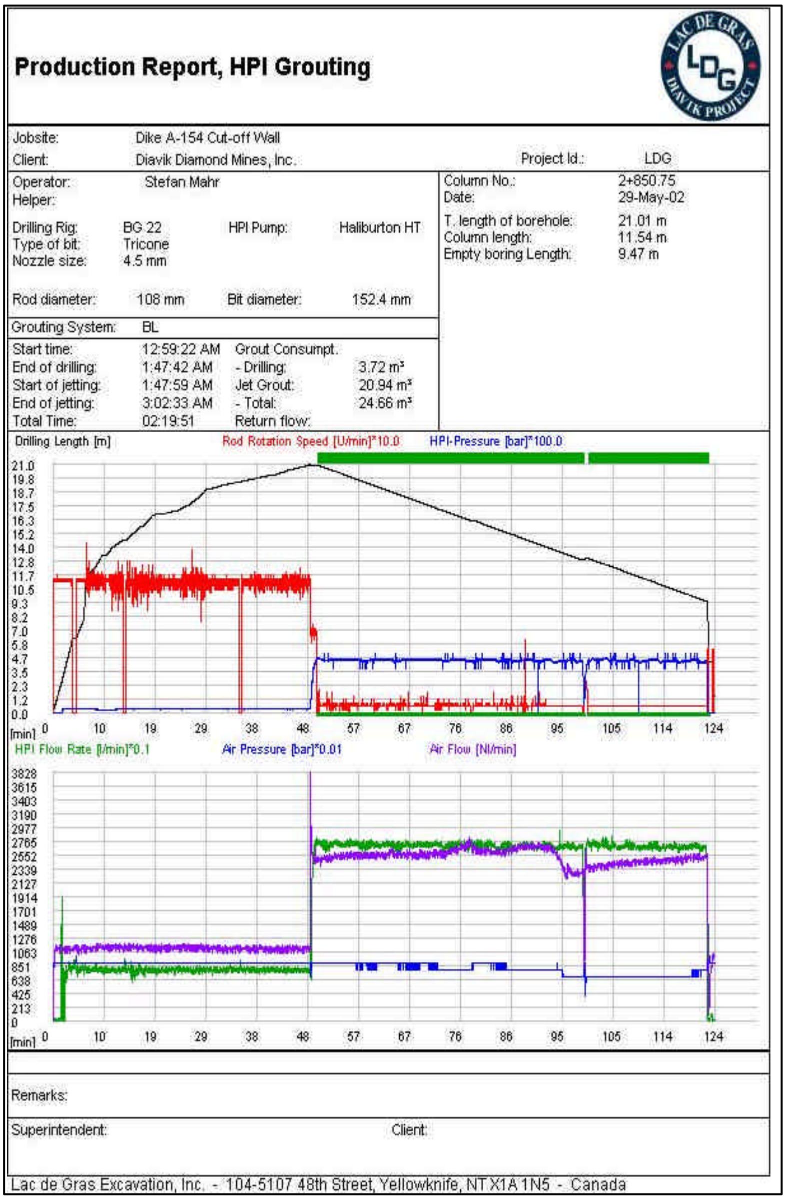

Fig. 14: Example of an electronically-generated jet grouting record

The individual data records were combined electronically in an “as-Built Drawing”, which graphically represented the overlap of the diaphragm wall elements and the jet grout columns. The connection to bedrock was also shown, and the overall drawing documents considerably eased the analysis and quality control efforts required.

6. Conclusions

Installation of the last jet grout column was completed in mid-July 2002, weeks ahead of the scheduled completion date. Ten days after that, pumping out of the dike pool began, followed by the stripping of till from the planned mining area inside the dike. The high quality of the cutoff wall system resulted in a seepage rate of only 800 liters per minute for the entire dike. As a consequence, no repair work on the cutoff was required.

By late November 2002, the first diamonds were recovered, and by December 2002 regular diamond production began. In January 2003, the first diamonds were shipped, 3 months ahead of schedule. In future years, the A418 and A21 kimberlite pipes will be isolated from the main lake by other dikes, and on-going diamond production will be continued.

Fig. 15: Dike pool dewatered – October 2002

7. Bibiliography

Diavik Diamond Mines Inc., web page www.diavik.ca.

Photos: employees of Diavik Diamond Mines Inc., Lac de Gras Constructors, Nishi-Khon SNC-Lavalin and Bauer Machinen GmbH