INNOVATIVE MINE PROJECTS USING ARTIFICIAL GROUND FREEZING (AGF) ON A LARGE SCALE

J. Sopko
Director-Ground Freezing
Keller-North America
New Jersey, USA

*F. A. Auld
Retired Consultant
Doncaster UK
*(*Corresponding author: faauld@btinternet.com)*

ABSTRACT

This paper reviews past mine projects where an innovative approach has been adopted using Artificial Ground Freezing (AGF) on a large scale for their successful completion. Although patented by H. Poetsch in 1883, AGF was first used for mine shaft construction in South Wales in 1862, providing temporary ground support and groundwater ingress control during sinking. Since then, the process has been applied on a large-scale basis worldwide in the mining field for stabilizing groundworks and underground construction over many years. The importance of the process of AGF in the mining world cannot be overstated. In fact, without ground freezing in many cases, such construction works would not have been possible.

The paper will cover projects in Canada and the USA, describing the problems faced and how they were successfully overcome.

Final summary comments complete the paper.

KEYWORDS

Artificial ground freezing (AGF), shaft construction, ground support

INTRODUCTION

Artificial ground freezing for shafts and tunnels related to subway, water, and sewer projects has been the focus of many articles and conference topics in recent years. However, few readers know that this technique to provide temporary earth support and groundwater control originated in the mining industry in the late 1800s.

Although patented by H. Poetsch in Germany in 1883, artificial ground freezing (AGF) was adopted for mine shaft construction in South Wales in 1862, providing temporary ground support and groundwater ingress control during sinking. Since then, the process has been applied globally in the mining field for deep shaft and surface drift construction. Many innovative projects have only been successful with the adoption of AGF, exemplifying the importance and substantial value of AGF in the mining world over many years. Some of these projects have been designed and constructed, but a few innovative ideas have led to complex pilot tests that confirm the technical feasibility of ground freezing on very large scales.

Cameco's Cigar Lake Mine in Canada is one of the largest ground freezing projects completed (Newman et al.). More detail is present in additional papers in the symposium proceedings. While the author has little knowledge of Cigar Lake, he has intimate knowledge of the following projects discussed. There is an interesting observation when reviewing each of these.

Most ground freezing projects have several things in common, no matter how complicated. Freeze pipes are typically one meter apart and must have minimal deviation; the circulating brine is usually around -32 ºC, and freezing takes four to ten weeks. Those parameters are not meant to oversimplify the design and construction process but can be considered relative "rules of thumb." The following projects were all constructed with similar parameters related to spacing, temperature, and time, but each one had a unique concern that governed the design or required modification during the operations.

Crown Pillar Excavation Project – Rouyn-Noranda, Quebec.

The Quemont Mine in Rouyn-Noranda, Quebec, was completed and closed several decades ago. Left in its place was a crown pillar known to contain approximately 11,000 m^3 of zinc. The deposit was 24 to 37 m (78 to 121 ft) below water-bearing unconsolidated mine tailings and very soft clay. Mining from the surface had been considered for several years; however, technically and economically, excavation support was the limiting factor.

After evaluating several open-cut options with very narrow slopes and potential dewatering, one large excavation was considered. The concept called for a large frozen earth wall to provide temporary earth support and groundwater control. The problem unique to this project was time-dependent creep deformation. While creep deformation has governed the design of many deep mine shafts, it is typically mitigated with specially designed temporary liners.

This project required a final design to support a 61 m diameter circular excavation to a depth of 30 m. Laboratory tests indicated that the clay material had a very high water content and was susceptible to creep deformation when frozen. Different from the many deep shafts constructed in Europe and Canada, the size of this project prevented the construction of a liner as the excavation progressed.

Frozen earth compression and creep tests were conducted to evaluate the time-dependent strength and deformation (Sopko et al. 2012). This evaluation concluded that the service life of the proposed frozen earth cofferdam would be limited due to the creep characteristics of the frozen clay. Evaluation of the excavation, blasting, and mining schedule indicated that the mining operation could be completed in three months. If the project would be successful, it was agreed that to maintain a safe excavation, it would be necessary to limit the internal stresses to 733 kN/m^2. Using active earth pressures and full hydrostatic load from the ground surface, internal stresses could be limited to 733 kN/m^2 if the frozen earth wall was no less than 9.15 m thick.

A 10m frozen earth wall was designed to compensate for the long-term creep potential. Additionally, the excavation time was limited to 120 days.

Figure 1. Freeze pipe configuration

The freezing operation started in September and was specifically coordinated so that excavation would begin in early January when temperatures were known to be well below freezing.

Figure 2. Excavation process of crown pillar

Excavation proceeded from January through March. As the ambient air temperatures started warming, sloughing of the south wall was observed in an area exposed to direct sunlight. Large concrete blankets were hung from the surface to protect the face of the frozen earth wall. While they helped somewhat, ambient temperatures increased as mining operations continued. During early April, a severe thunderstorm occurred, and lightning damaged the transformer for the refrigeration plants. It was decided to begin backfilling and terminate the project with minimal ore left in the excavation.

Aquarius Gold Mine – Timmins, Ontario

While many large-scale AGF projects have been conceived, the first field implementation (but not completed) was the Aquarius Gold Mine in 1996. The Aquarius property was originally owned by Asarco and started as an underground mine in the 1970s. High groundwater inflows required the Asarco to abandon the mine, which was sold to Echo Bay Mines. In 1996, Echo Bay proceeded with plans to mine the gold from a large open pit with a conventional approach using high-capacity dewatering wells around the 4-km (2.5-mile) perimeter. Hydrogeological studies indicated that this massive dewatering program had the potential to deplete the water in several small lakes at a provincial park adjacent to the project and several residential wells.

A frozen earth barrier was proposed and installed around the 4-km (2.5-mile) perimeter. The ground freezing system had 2,335 individual 8.9 cm (3.5-in.) diameter freeze pipes into the underlying bedrock. The spacing between pipes varied depending on the depth to the underlying bedrock to compensate for deviation during drilling. In some locations, the bedrock was as shallow as 42 m (140 ft) but could be as deep as 153 m (505 ft) at locations on the east side of the project. Pipes at the shallower depths were spaced approximately 2 m (6.5 ft) apart, while deeper ones were spaced at 1 m (3.2 ft). Since the pipe's deviation during drilling increased with depth, the shallower pipes would have less deviation and could be placed further apart at the ground surface.

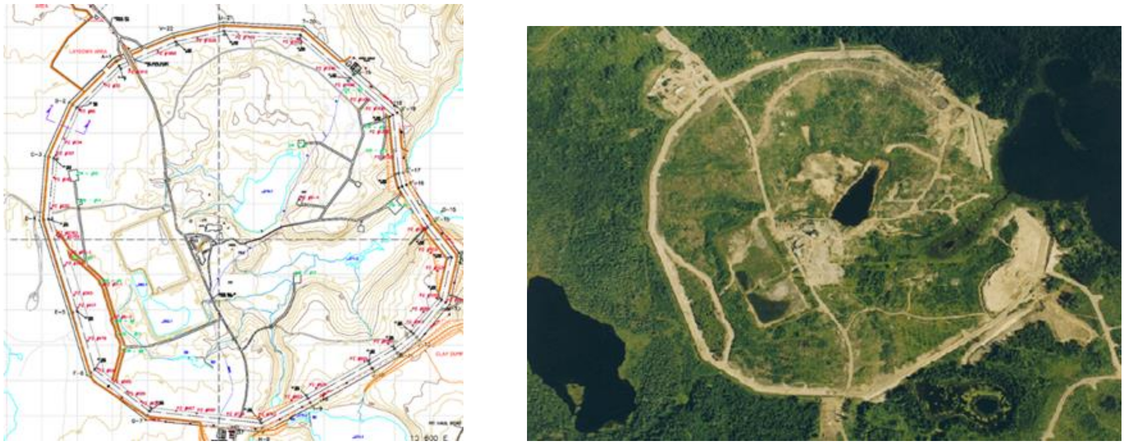

Figure 3. Aquarius Mine ground freezing system

The refrigeration system was based on two permanent buildings at the north and south ends of the frozen barrier. Each building had five 900-hp compressors for a combined capacity of 8800 kW of refrigeration. The large compressors used ammonia as the primary refrigeration gas that cooled the circulating calcium chloride brine.

The circulating coolant system was a unique challenge to this project. While the freeze pipe spacing and refrigeration capacity were readily evaluated using thermal modeling, each freeze pipe required a minimum of 4550 l/hour of the refrigerated calcium chloride brine. The coolant distribution manifold was divided into four sections, each approximately 1 km long. The overall requirements for the hydraulic design of this system were based on the following:

- 2335 individual freeze pipes grouped in series into circuits.
- 574 circuits.
- 304m of freeze pipe in each circuit.
- Two to seven freeze pipes per circuit, depending on pipe depth.
- 4000m of above-grade piping
- 965 kPa pressure drop for each 1km section.

To ensure a balanced flow through each pipe or circuit, it was necessary to have a supply, return, and reverse return (balancing) distribution manifold as shown in Figure 4.

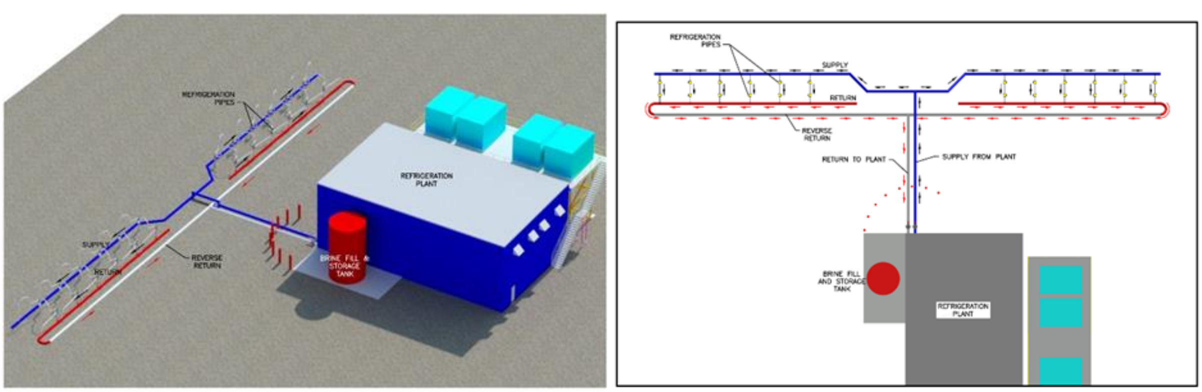

Figure 4. Reverse return balancing manifold

As the installation of the ground freezing system was nearing completion, gold prices fell to below $300/oz (US). The freezing system was completed, tested, and put into standby mode. For four consecutive years, the system was started up and tested. During that time, the gold price remained too low to justify the expense of operating the ground freezing system and mining the ore. It was eventually abandoned. While only partially operational, the Aquarius ground freezing system provided sufficient data to confirm that ground freezing systems could be installed on large-scale projects.

Underground Heating of Oil Shale - Shell MIT project.

The Mahogany Isolation Project (MIT) was a pilot test conducted near Meeker, CO, to evaluate the effectiveness of a frozen soil barrier used with high-temperature heating of oil shale. Shell's process used in situ heating of the oil shale that converts the kerogen to shale oil. Heating probes were installed into boreholes and warmed to approximately 662 °F (350 °C). This heating would result in the conversion of the shale to oil. After this conversion, the oil would be pumped to the surface. In the early stages of the testing, it was observed that the groundwater present within sand seams in the shale would cool the probes, preventing them from reaching the required temperature. Additionally, toxic by-products and gases would form, requiring the isolation of the process from the groundwater.

The concept of creating a frozen earth barrier around multiple probes was considered as a method to both prevent the inflow of groundwater and isolate the toxic by-products until remediated. A pilot test was conducted to evaluate the effectiveness of a frozen earth barrier.

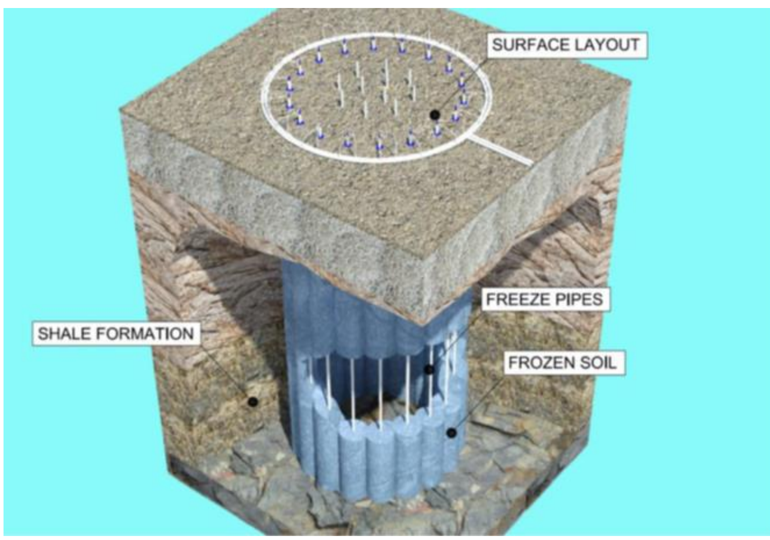

Figure 5. Schematic of Mahogany Isolation Test

There were 18 freeze pipes, two temperature monitoring pipes, and seven groundwater instrumentation borings drilled to approximately 381 m (1,250 ft). Two heating and one oil extraction well were installed in the interior of the frozen cell. Freezing was completed using 400 t (450 st) of refrigeration.

Figure 6. Mahogany Isolation Test

The remoteness of the site added significant logistical issues for a ground freezing operation. Diesel-powered generators were used to provide the 1,500-kw power required. The mobile refrigeration plants had water-cooled condensers requiring water to be delivered to the site daily. The freezing process was longer than initially anticipated due to a geothermal gradient that had yet to be previously identified. The successful project led to an additional test of a larger area.

Figure 7. Second phase of the Mahogany Isolation Test

Shell's long-term commercialization plan of the heating and freezing would encompass hundreds of square miles of Colorado, Wyoming, and Utah. The large grids of the heating elements and extraction wells within frozen earth barriers were considered an approach to tapping into the large oil reserves within the oil shale.

The unique concern of this project was the drilling requirements. Due to the depth of the freeze pipes, directional drilling was required. While the project would have been straightforward with the use of conventional mud motors, environmental concerns prohibited the use of drilling mud. Instead, high-pressure air was used to advance the system. Evaluation after the project completion indicated that in some strata, the air may have evacuated groundwater required to form a continuous frozen earth wall.

Another interesting observation on this project that should always be a concern is what can happen when internal or contracted design, procurement, and construction management firms replace qualified and experienced ground freezing contractors and engineers. Often, these firms need more practical knowledge to design and construct ground freezing systems. On this project, an entire division was created to manage the freezing process internally for the oil company. The costs of transforming the ground freezing technology from testing to commercialization had increased substantially from the original estimates prepared by the freezing contractor, thus making it economically unfeasible.

Groundwater Barrier – Fort Hills Basal Aquifer Confinement, Alberta, Canada

Another large and ambitious frozen barrier concept was a frozen earth barrier for the Fort Hills Oilsands Project. The basal aquifer had excessively high salinity and intrusion of the saline water into the mine, resulting in difficulty of the ore processing. Treatment of the water was cost-prohibitive, making the barrier concept quite attractive. Different considered approaches included a hydraulic barrier imposed by a series of high-capacity upstream wells, a slurry wall, and a cementitious grouted wall.

The volume of water produced by the wells had excessive treatment and discharge requirements and was not considered practical. Slurry walls and cementitious grouting left a permanent structure in the ground that would disturb the natural groundwater regime in perpetuity. The concept of a frozen earth barrier was considered, and despite the large energy requirements appeared to be a technically feasible approach.

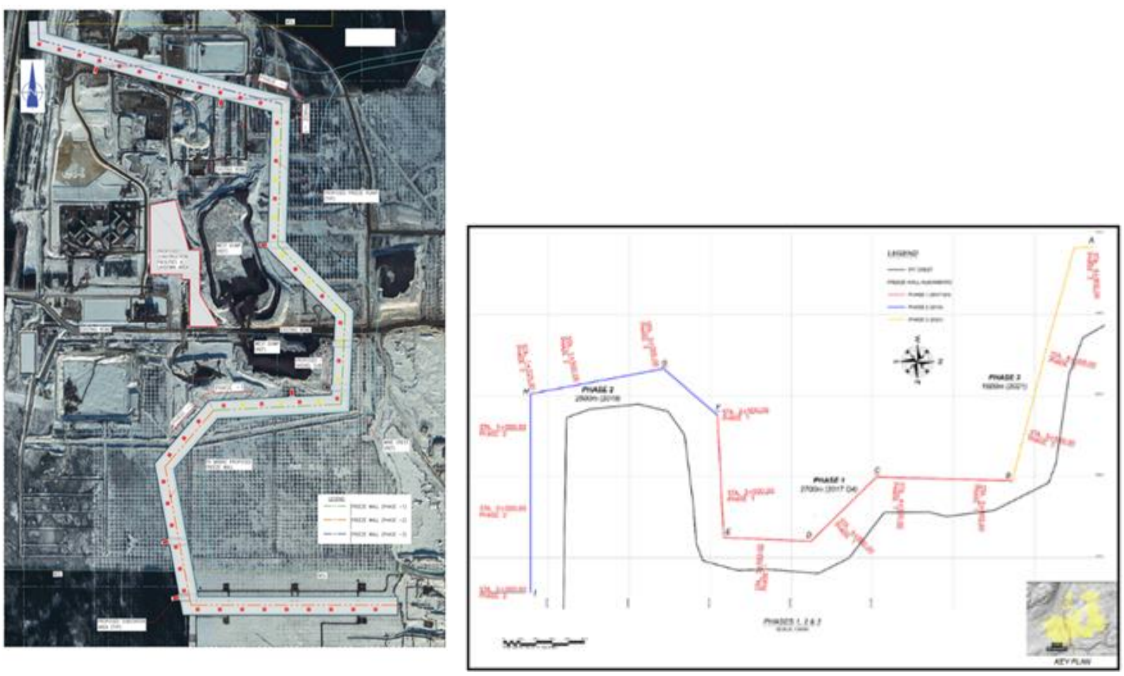

Figure 8. Proposed frozen earth barrier

The proposed project had a frozen wall length of 6.8km. This included 4,534 freeze pipes drilled to depths of 160m. Since the frozen earth concept had never been attempted or tested in the oil sands or basal aquifer, the owner's engineers and geologists designed a ground freezing pilot test. The pilot test was a simple circular freeze pipe arrangement, as shown in Figure 9.

Figure 9. Basal aquifer ground freezing pilot test

The objectives of the pilot test were:

- Verify that the highly saline basal sands could be frozen.
- Test different materials for freeze pipes to economize on the large-scale project.
- Evaluate freeze pipe configurations to isolate the frozen zone to only the basal sands.
- Confirm thermal modeling parameters.

The pilot test met all the objectives and requirements and was highly successful. The project then moved into the design phase of the large, full-scale barrier. The unique concern of this project was the groundwater gradient initiated by the mining process and the potentially high groundwater velocity that would result. High groundwater velocity can retard, or even prevent the formation of a frozen earth structure. While high groundwater velocity is not unique to ground freezing, it is typically an unexpected hindrance. In this case, the frozen barrier had to be designed with a groundwater velocity as a baseline. Extensive thermal modeling, coupled with groundwater flow, was conducted to eventually propose a frozen earth barrier with multiple rows of freeze pipes.

As with other mining projects discussed, the ore (oil) price fell during the design and evaluation of the frozen earth barrier. This price decrease in price made the ground freezing option economically unfeasible. The mine proceeded; however, the area affected by the saline water was not mined.

SUMMARY

The projects presented demonstrate the potential of ground freezing when used on a large scale. While ground freezing was technically feasible in all cases, the high costs associated with full-scale production or commercialization prohibited its implementation. Unlike shafts or tunnels, these large-scale projects could operate for ten to twenty years or longer. Electrical power becomes the most significant cost factor in the long-term operation. The high-power requirements will never be met with renewable energy technology such as wind or solar-generated electricity. However, recent technology is emerging that will permit the implementation of small-scale nuclear power plants. These plants will provide the required energy at significantly lower prices. Should this technology be available, the potential for ground freezing on large-scale projects will be unlimited.

REFERENCES

Jaffe, M. 2013. Shell Abandons Western Slope Oil-Shale Project. The Denver Post.

Newman, G., Newman, L., Chapman, D., and Harbict., T. (2011). Artificial Ground Freezing: An Environmental Best Practice at Cameco's Uranium Mining Operations in Northern Saskatchewan, Canada. Proceedings: IMWA, Aachen, Germany.

Sopko, J., Braun, B., Chamberland, R., (2012). Largest Frozen Ground Excavation in North America for Excavation of Crown Pillar. Proceedings: International Conference on Shaft Design and Construction. London, United Kingdom.