GROUND FREEZING ON A LARGE SCALE AND ITS HISTORICAL IMPORTANCE IN DEEP MINE DEVELOPMENT

Sopko, J. Director-Ground Freezing, Keller-North America

Auld, F. A. Consultant, Golder/WSP

ABSTRACT

Artificial ground freezing for shafts and tunnels related to subway, water, and sewer projects have been the focus of many articles and conference topics in recent years. Few readers are aware however, that this technique to provide temporary earth support and ground water control, originated in the mining industry in the late 1800s. The first documented project was a coal mine in Wales. Another unknown fact is the magnitude of ground freezing projects on mining projects. This article reviews past mine projects throughout the world where ground freezing was essential for successful shaft sinking and surface drift construction. It mentions other innovative mine projects where again it was necessary to adopt ground freezing to enable the projects to be undertaken and three of these are discussed in more detail. Projects of the magnitude in mining works require specialized design and analysis techniques that are reviewed. The construction methods and quality assurance programs are emphasized. The projects discussed show how innovative methods set records for projects on a very large scale.

INTRODUCTION

Although patented by H. Poetsch in Germany in 1883, artificial ground freezing (AGF) was first adopted for mine shaft construction in South Wales in 1862 where it was used for providing temporary ground support and ground water ingress control during sinking. Since then, the process has been applied on a large-scale basis throughout the world in the mining field for deep shaft and surface drift construction over many years. In addition, innovative projects have been undertaken where success could only have been achieved with the adoption of AGF. The importance of the process of AGF in the mining world in facilitating the means of access for the extraction of minerals from underground therefore cannot be overstated. In fact, without the use of ground freezing, in many cases, the construction of mine shafts and surface drift projects would not have been possible. This paper will review previous mine deep shaft and surface drift construction where AGF was involved and will also describe the innovative projects.

MINE SHAFTS

UK Coal Mine Shafts

The German freezing system was introduced into England about the year 1900 and successfully employed in some shaft sinkings (Neelands 1926). An English company, known as the Shaft Freezing Company with headquarters at Selby, Yorkshire, was formed to exploit the process. In 1912, a contract was given to the Shaft Freezing Company to bore the freezing holes and carry out the freezing, sinking and lining of two 22ft ID shafts to be sunk to 500m depth at Thorne Colliery, South Yorkshire. The freeze holes were drilled, cased and the inner inlet tubes installed but the outbreak of the First World War in 1914 put an end to the activities of the Shaft Freezing Company and the German operatives who were unsuccessful in returning to Germany were interned. New mine projects at the time were halted for the term of the War to concentrate activities on the producing pits and war munition factories. After the Armistice, in November 1918, the freezing process was abandoned, due to the difficulties in resetting up the contract with the German company, and the work was completed using the cementation process for ground stability and water ingress control.

Table 1 lists the deep mine shafts constructed in the UK between 1947 and 1960 (Wild and Forrest 1981). The location and freezing depths are shown with the maximum freeze depth indicated as 268m.

	Location	*Freezing Depth*
1947-1949	Calverton No. 2 Shaft	1 shaft x 125 m
1952-1955	Bevercotes Nos. 1 and 2 Shafts	2 shafts at 248 m and 250 m
1952-1955	Lea Hall Nos. 1 and 2 Shafts	2 shafts at 218 m and 222 m
1954-1957	Cotgrave	2 shafts at 268 m each
1956-1957	Hawthorn Shaft. Co. Durham	U/G freeze, 1 shaft, 76 m to 137 m
1956-1959	Wearmouth 'D' Shaft, Co. Durham	1 shaft x 108 m
1958-1960	Kellingley Nos. 1 and 2 Shafts	2 shafts at 195 m each

Table 1. UK shafts using ground freezing for temporary support (Wild and Forrest 1981)

During 1968-1974 two 5.486m ID shafts were sunk to 1150m at Boulby, North Yorkshire, for the Cleveland Potash Mine (Cleasby et al 1975). Presently they are the deepest shafts in the UK. Two different methods were used to overcome the high-pressure saline water in the Sherwood Sandstone. The grouting and tubbing method was adopted for the No. 2 shaft and the freezing and steel lining method was used in the No. 1 shaft (Figure 1). For the freezing method, the drilling of the freeze holes from surface to a depth of 1000m and the deflection of these holes into positions later to be intersected by an underground freeze chamber at 590m was successfully achieved.

Between 1977 and 1986, six shafts were sunk by Cementation Mining Ltd for the Selby Coalfield Project in North Yorkshire, UK (Figure 2). These were at Wistow, Riccall and North Selby. Thyssen Mining (GB) Ltd sunk the other four at Stillingfleet and Whitemoor. In the No. 1 shaft at Wistow the freeze depth was 273m to provide groundwater ingress control through the Bunter Sandstone and Lower Magnesian Limestone plus ground stability control through the Basal Sands. In all the other cases, the freeze depths ranged from 148m at the Wistow No. 2 shaft site to the deepest at 305m in the case of Whitemoor to provide groundwater ingress control through the Bunter Sandstone. All the Selby shafts were 7.315m ID (24ft).

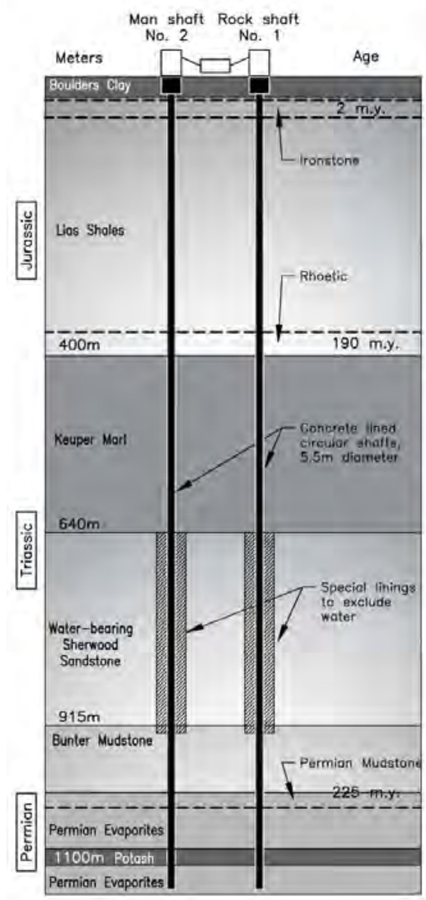
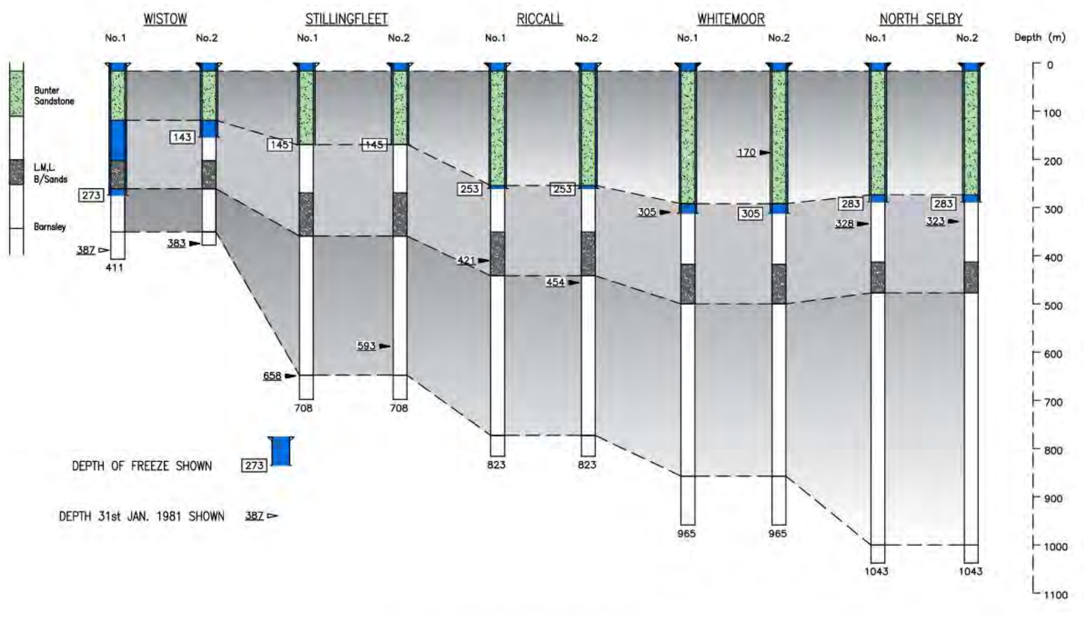


Figure 1. Boulby Potash Mine. Sratigraphic section (Williams and Auld 2002)

During 1985-1989 two 7.315m ID shafts were constructed by Cementation Mining Ltd for British Coal's Asfordby Mine, near Melton Mowbray in the NE Leicestershire UK coalfield. These shafts were sunk through the heavily water bearing Bunter Sandstone formation (Figure 3). The operation entailed a sub-surface freeze from a level 275m below surface and extended to 405m depth. This approach required precise freeze hole drilling and surveying, construction of an underground working chamber to locate and furnish the freeze holes and a comprehensive monitoring system. Thirty-nine freeze holes were drilled for each shaft on a 16.1m PCD. Due to numerous surface limitations, such as pile foundations, fifteen holes were directionally drilled from an adjacent hole's surface position and top hole section (Figure 4).



SELBY COALFIELD DEVELOPMENT

Figure 2. Selby Coalfield shafts (Tunnicliffe and Keeble 1981)

Canadian Potash Mine Shafts

Of the 21 shafts sunk for the Saskatchewan potash industry since the 1950's, five early ones had major water inflow problems and one even had to be abandoned during the sinking process. To address the problem, ground freezing was adopted for the construction of subsequent shafts. Table 2 lists a number of these shafts. The greatest obstacle which shaft sinkers faced was a succession of water-bearing formations, as many as ten in some areas, all the way from the glacial till near the surface to the Dawson Bay dolomites just above the salts of the Prairie Evaporite formation. Of these water-bearing formations, the one to prove the most difficult was the Blairmore (Figure 5). It ranges in thickness from 60m (197ft) to 150m (492ft) and occurs at a depth from 375m (1230ft) to 440m (1444ft) in the Esterhazy area and from 520m (1706ft) to 640m (2100ft) west of Saskatoon. It consists of unconsolidated water-bearing sand, clay, shale and silt under pressures of up to 6.5 MPa.

Prior to 1963, the established freeze hole drilling technique was either a modified percussion method developed early in the century in Europe, or the standard rotary method with whipstocks. Both methods had serious limitations, even at shallow depths at which they were employed. It was felt that a new technique could greatly improve the efficiency with which freeze holes could be drilled, especially since depths in excess of 610m (2000ft) were expected in the potash fields in western Canada. In 1963 Precision Drilling Co. Ltd, together with Eastman Oil Well Survey Co. of

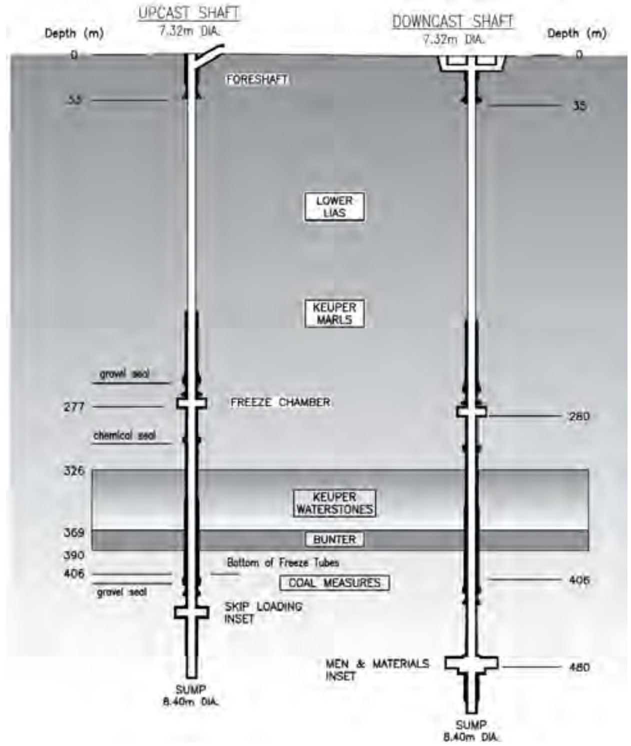


Figure 3. Asfordby Mine. General geological section through the shafts (Harvey and Martin 1988)

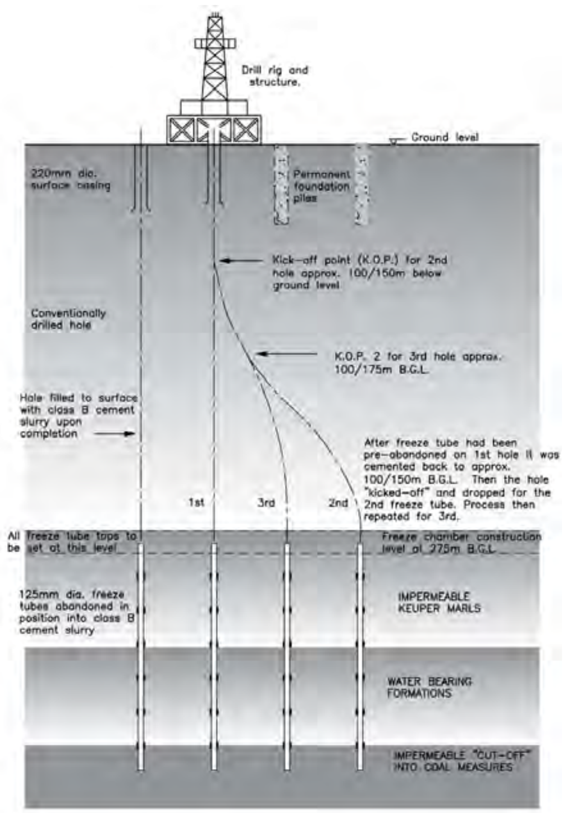


Figure 4. Asfordby Mine. Schematic description of directionally drilled freeze holes Harvey and Martin 1988)

Project	Client	Contractor	Internal Diameter m (ft)	Depth m (ft)	Freeze Depth m (ft)	Date
Esterhazy (Yarbo) K1 and K2	International Minerals Corporation (IMC)	Cementation Co. (Canada) Ltd	No.1 shaft 5.486 (18)	1029.6 (3378)	No. 2 shaft 467.9 (1535)	1957-1962
Vanscoy No. 1 Production) and No. 2 (Service) shafts	Cominco Ltd	Cementation Co. (Canada) Ltd	No. 1 shaft 5.639 (18.5) No. 2 shaft 4.877 (16)	1143.6 (3752)	684.3 (2245)	1963-1967
Cory No. 1 and No.2 shafts	Duval Corporation	Cementation Co. (Canada) Ltd	No. 1 shaft 4.877 (16) No. 2 shaft 4.877 (16)	1023 (3356)	592.5 (1944)	1963-1967
Patience Lake No. 1 and No. 2 shafts	Potash Corporation of Saskatchewan (PCS)		No.1 shaft 16 (4.877) No.2 Shaft	No.1 shaft No.2 shaft 950 (3120)	27 FT's to 609.6 (2000) 16 FT's to 914.4 (3000)	No.1 shaft 1956-1958 (then rehabilitated 1959 – 1965) No.2 shaft 1966-1969
Allan No.1 and No. 2 shafts	Potash Corporation of Saskatchewan (PCS)		No. 1 shaft 4.877 (16) No. 2 shaft 4.877 (16)	1086 (3565)		1964-1968
Lanigan (Alwinsal) No. 1 Production and No. 2 Service shafts	Potash Corporation of Saskatchewan (PCS)	Associated Mining Construction (AMC)	No. 1 shaft 5.5 (18) No. 2 shaft 4.32 (14)	No.1 shaft 863 (2831) No. 2 shaft 855 (2805)		1967-1969 (No. 1) 1973-1979 (No. 2)
Rocanville No.1 Production and No.2 Service	Potash Corporation of Saskatchewan (PCS)	Associated Mining Construction (AMC)	No. 1 shaft 4.93 (16.2) No. 2 shaft 4.93 (16.2)	No. 1 shaft 930 (3051) No. 2 shaft 928 (3045)		1967 - 1969
Scissors Creek (Rocanville West expansion project)	Potash Corporation of Saskatchewan (PCS)	Associated Mining Construction (AMC)	6 (19.685)	1123 (3684)	32 FT's to 580 (1903)	2010-2015
Esterhazy K3 shafts	Mosaic Company	Associated Mining Construction (AMC)	No. 1 shaft 6.5 (21.325) No. 2 shaft 6.5 (21.325)	1021.1 (3350)		2009-2012
Jansen No.1 and No.2 shafts	BHP Billiton	DMC	No. 1 shaft 6.5 (21.325) No. 2 shaft 6.5 (21.325)	975	720 (2362)	2016-2020

Table 2. Saskatchewan Potash Shafts

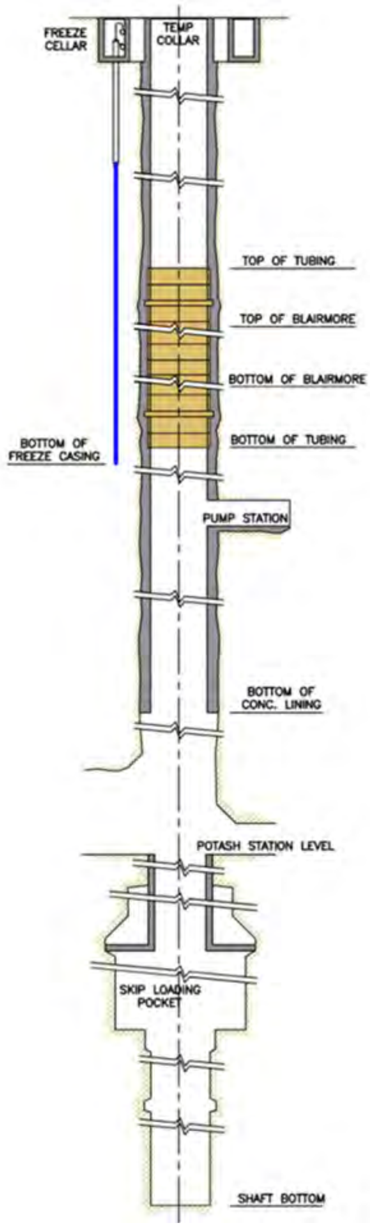


Figure 5. Cominco Vanscoy No. 1 shaft section (Kelland and Black 1969)

Canada, undertook the drilling of a hole at Esterhazy, Saskatchewan, for International Minerals Corporation to test the feasibility of turbo-drilling in conjunction with rotary drilling for deep freeze hole application (Adamson and Storey 1969). The over-riding criterion in the test hole specification was the limited tolerance specified for deviation. A target of 305mm (1ft) radius over the whole length of the hole was chosen as the deviation limit for the exercise. The test hole was completed to a depth of 467.3m (1533ft) within the target area, except for two short sections which fell just outside the 305mm (1ft) radius limit. Surveying of the hole was carried out at 9.1m (30ft) intervals with the Eastman single-shot magnetic equipment. The Cominco Vanscoy No. 1 shaft freeze hole survey is shown in Figure 6.

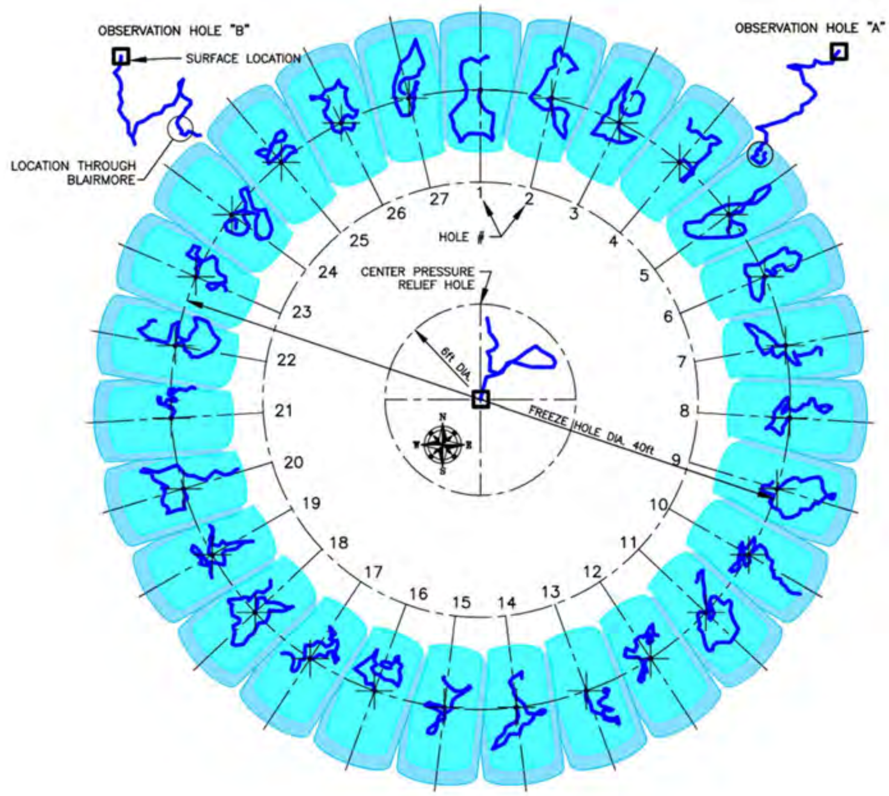


Figure 6. Cominco Vanscoy No. 1 shaft freeze hole survey (Kelland and Black 1969)

German Coal Mine Shafts

The importance of the use of ground freezing for shaft sinking in the West German coal mining industry is again demonstrated by the 10 shafts constructed between 1980 and 1990 (Figure 7). German ground conditions consist of unstable sands, silts and clays down to depths of around 600m (1969ft) in some cases and require a specially designed "sliding" lining system as temporary ground support to accommodate freeze wall deformation before the permanent lining can be installed upwards from the bottom (Figure 8). The concrete blocks with chip boards (squeeze packs) allow the large freeze wall deformations to be carried while the inner lining is constructed.

Chinese Coal Mine Shafts

Zhang et al 2012 report that over 600 shafts have been sunk in China using ground freezing for temporary support. The thickest sinking through alluvium was 587m (1926ft) with a freezing depth of 800m (2625ft). Table 3 lists some of these shafts.

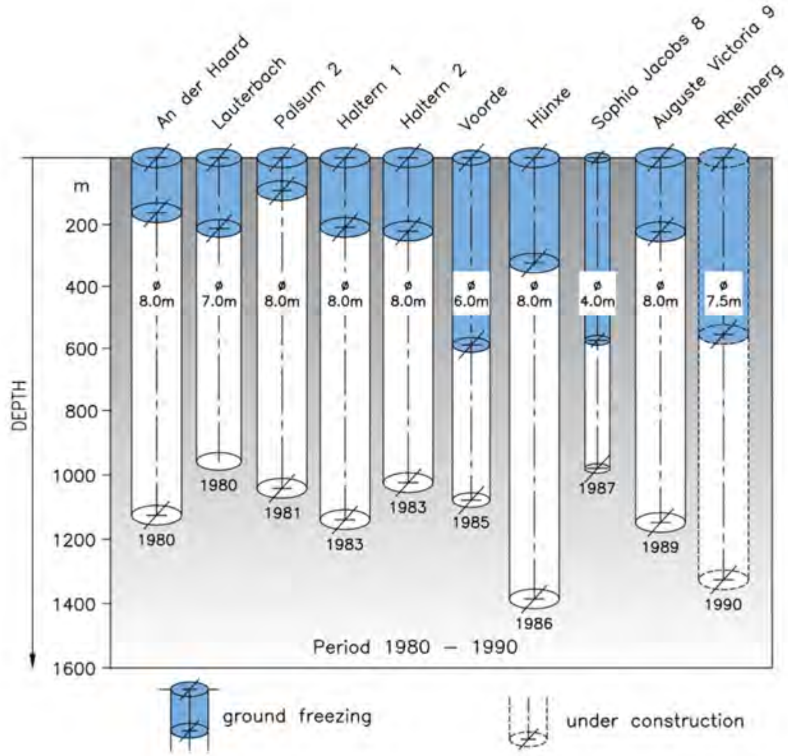


Figure 7. German coal mine shafts constructed between 1980 and 1990 (Klein 1989)

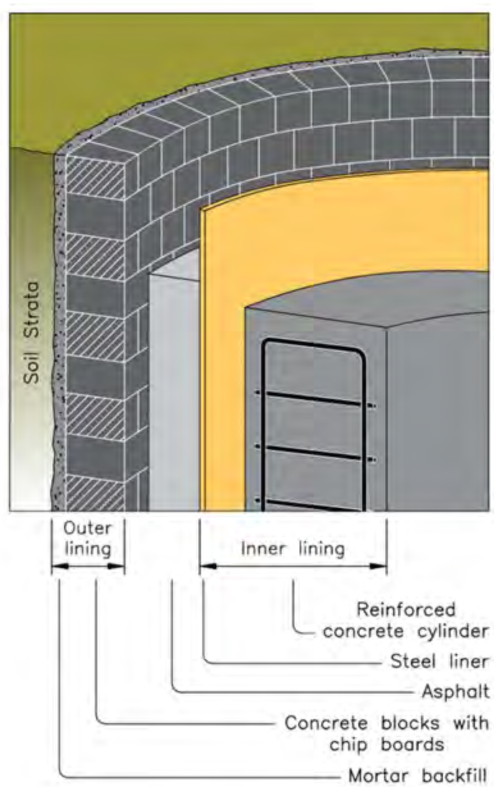


Figure 8. German "sliding" lining system through unstable frozen ground (Stoss and Braun 1983)

Shaft wall structure and parameter			
Shaft #	Shaft description	Freezing depth (m)	Max. grade of concrete
1	Chengcun Mine auxiliary shaft	485	C70
2	Longgu Mine main shaft	640 (shaft drilling)	C70
3	Wuguiqiao Mine auxiliary shaft	420	C60
4	Quandian Mine main shaft	513	C70
5	Quandian Mine auxiliary shaft	500	C75
6	Quandian Mine air shaft	523	C75
7	Zhaogu No. 1 Mine main shaft	575	C70
8	Zhaogu No. 1 Mine aux. shaft	575	C80
9	Zhaogu No. 1 Mine air shaft	575	C80
10	Zhaogu No. 2 Mine main shaft	615	C80
11	Zhaogu No. 2 Mine aux. shaft	628	C90
12	Zhaogu No. 2 Mine air shaft	628	C90

Table 3. Chinese coal mine shafts sunk using ground freezing for ground stabilisation and prevention of groundwater ingress during shaft sinking (Zhang et al 2012)

MINE SURFACE DRIFTS

Selby Gascoigne Wood Mine Surface Drift

The drift was driven through Basal Sands which were known to be weakly cemented and when water is allowed to flow through them the sands also flow. To provide the necessary ground support and groundwater ingress prevention, a single line of vertical freeze holes was drilled and kicked off alternatively to form a tent of frozen ground over the drift (Figures 9 and 10). At the time, the method adopted was believed to be the first of its kind in the world.

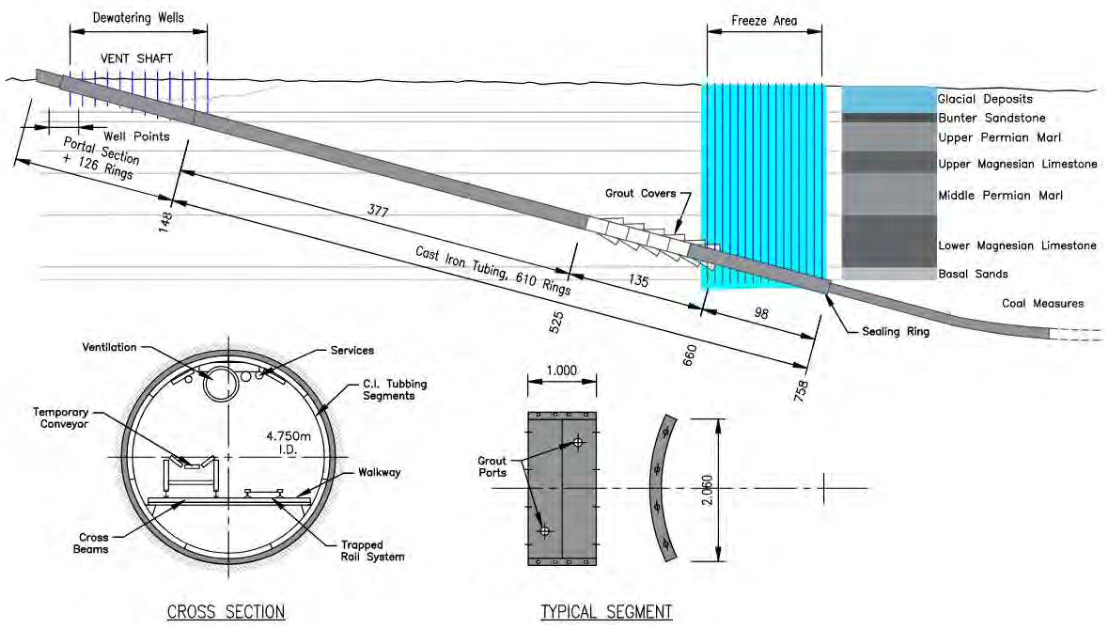


Figure 9. Ground freezing for Selby Gascoigne Wood Mine Surface Drift (Forrest and Black 1979)

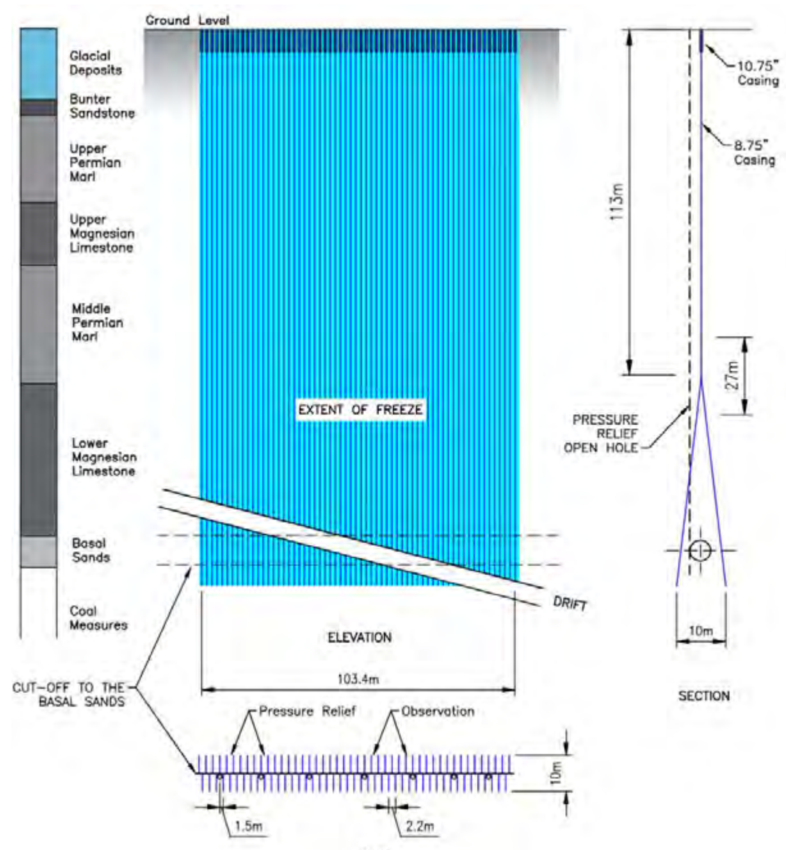


Figure 10. Ground freezing for Selby Gascoigne Wood Mine surface drift (Forrest and Black 1979)

INNOVATIVE MINE PROJECTS

Apart from the shaft sinking and surface drift construction projects, several innovative mine projects have been considered or successfully completed only with the help of artificial ground freezing:

1. Anaconda Minerals Underground Oil Platform, Alaska, USA

In 1984 the concept was to recover heavy oil from the shallow deposits on the North Slope of Alaska by using artificial ground freezing to enhance the 609.6m (2000ft) of permafrost. Shafts could then be sunk to a depth of 1219m (4000ft) to enable the oil to be extracted by drilling from an underground mine environment. The project did not go ahead because of the drop in oil price at the time and it became uneconomical to proceed.

2. Aquarius Gold Mine, Timmins, Ontario, Canada

3. Shell MIT Project, underground heating of Oil Shale, Colorado Basin, USA

4. Fort Hills, ground stability and water ingress prevention for opencast mining of Oil Shale, Alberta, Canada

In 2015 Suncor/TOTAL/Teck were in the process of developing an open pit mine at Fort Hills for the extraction of oil sands. To prevent the ingress of groundwater into the excavation, a cut-off barrier was being considered using ground freezing. This was a large-scale project involving many kilometres of freeze wall.

5. Cameco Cigar Lake Uranium Mine, Northern Saskatchewan, Canada

Ground freezing from the surface has been used to stabilize the ore body at depth to facilitate retrieval of the ore by drilling from underground tunnels.

6. Noranda Crown Pillar Excavation Project, Quebec, Canada

Three of these projects (2,3 and 6) are described in more detail in the following sections.

Aquarius Gold Mine, Timmins, Ontario, Canada

While many large scale AGF projects have been conceived, the first field implementation (but not completed) of this was the Aquarius Gold Mine in 1996 (see Figure 11 for surface area plan). The Aquarius property was originally owned by Asarco and started as an underground mine in the 1970's. High groundwater inflows required Asarco to abandon the mine at which time it 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 to use high-capacity dewatering wells around the 2.5-mile perimeter. Hydrogeological studies indicated that this massive dewatering program had the potential for depleting the water in several small lakes at a provincial park adjacent to the project, as well as several residential wells.

A frozen earth barrier was proposed and installed around the 2.5-mile perimeter. The ground freezing system had 2335 individual 3.5-inch 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 140 feet but could be as deep as 505 feet at locations on the east side of the project. Pipes at the shallower depths were spaced approximately two meters apart while the deeper ones were spaced at one meter. 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.

The refrigeration system was based on two permanent buildings located at the north and south ends of the frozen barrier. Each building had five, 900-hp compressors for a combined capacity of 5000 tons 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 major engineering challenge. Each freeze pipe required a minimum of 20 gpm of the refrigerated calcium chloride brine. To ensure a balanced flow, it was necessary to have a supply, return and reverse return (balancing) distribution manifold.

As the installation of the ground freezing system was nearing completion, gold prices fell to below $300/ounce (U.S.). The freezing system was completed and tested and put into a 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 never fully operational, the Aquarius ground freezing system provided sufficient data to confirm that ground freezing systems could be installed on large scale projects.

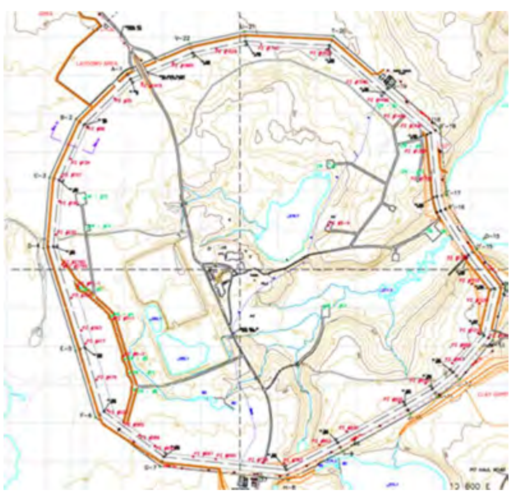


Figure 11. Aquarius Gold Mine, Timmins, Ontario, Canada – surface area plan

Shell MIT Project, underground heating of Oil Shale, Colorado Basin, USA

The Mahogany Isolation Project (MIT) was a pilot test conducted near Meeker, Colorado 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 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 during the heating 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. The initial pilot test is shown in Figure 12.

There were 18 freeze pipes, 2 temperature monitoring pipes and 7 groundwater instrumentation borings, drilled to depths of approximately 1250 feet. Two heating and one oil extraction well were installed in the interior of the frozen cell. Freezing was completed using a total of 450 tons of refrigeration.

The remoteness of the site added considerable logistic issues for a ground freezing operation. Diesel powered generators were used to provide the 1500kw power required. The mobile refrigeration plants had water-cooled condensers that required water to be delivered to the site daily.

The freezing process was longer than originally anticipated due to a geothermal gradient that had not been previously identified.

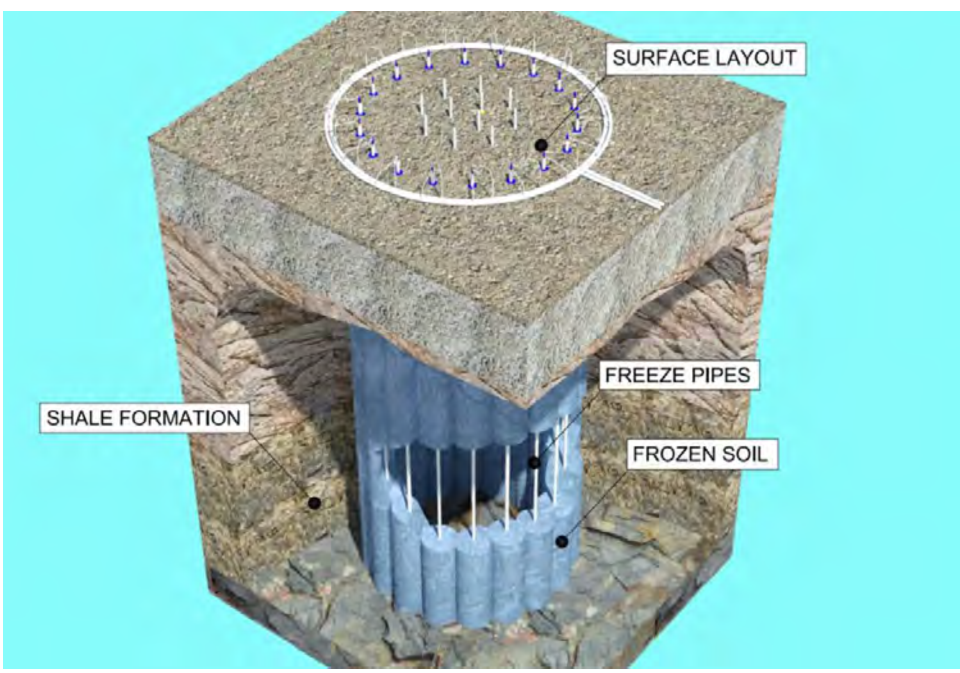


Figure 12. Shell MIT Project, Colorado Basin, USA – pilot test for underground heating of Oil Shale

Noranda Crown Pillar Excavation Project, Quebec, Canada

The Quemont Mine in Rouyn-Noranda, Quebec was completed and closed several decades ago. A crown pillar remained in place and was known to contain approximately 11,000 m^3 of zinc. The deposit was located 24 to 37 m below water-bearing unconsolidated mine tailings and very soft clay. Mining from the surface had been considered for several years, however excavation support was always considered to be the limiting factor, both technically and economically.

After evaluating several open-cut options with very narrow slopes and potential dewatering, the concept of creating one large excavation was considered. The concept called for a large frozen earth wall to provide temporary earth support and groundwater control.

The final design had a 61m diameter circular excavation to a depth of 30m (see Figure 13 for aerial view). Laboratory tests indicated that the clay material had a very high-water content and was susceptible to creep deformation when frozen. To compensate for the long-term creep potential, a 10m thick frozen earth wall was designed using three rows of freeze tubes (see Figure 14). Additionally, the excavation time was limited to 120 days.

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

Figure 13. Noranda Crown Pillar Excavation Project, Quebec, Canada, aerial view

Figure 14. Noranda Crown Pillar Excavation Project, Quebec, Canada - three rows of freeze pipes

SUMMARY

The review of previous mine shaft and surface drift construction on a worldwide basis has demonstrated how important the use of ground freezing has been in enabling the projects to be attempted and completed successfully. Innovation has also been a critical element in many mining projects, as demonstrated by the projects which have been reviewed. Without the use of ground freezing, none of the work described could have been achieved.

REFERENCES

Adamson, J. N. and Storey, J. H. 1969. Paper 19. Turbo-drilling as applied to potash developments in the Saskatchewan field. Ninth Commonwealth Mining and Metallurgical Congress. Mining and Petroleum Geology Section. Institution of Mining and Metallurgy. London. pp. 1-14

Cleasby, J. V., Pearse, G. E., Grieves, M. and Thorburn, G. 1975. Shaft-sinking at Boulby mine, Cleveland Potash Ltd. Transactions/Section A (Mining Industry), Vol. 84, January, Institution of Mining and Metallurgy. pp. A7-A28

Forrest, W. and Black, J. C. 1979. Hydrogeological analysis, ground treatment and special construction techniques at Selby Gascoigne Wood surface drift mine. Tunnelling '79 Symposium, 12-16 March. Institution of Mining and Metallurgy. London. pp. 3-10

Harvey, S. J. and Martin, C. J. 1988. Construction of the Asfordby Mine shafts through the Bunter Sandstone by use of ground freezing. The Mining Engineer. August. pp. 51-58

Kelland, J. D. and Black, J. C. 1969. Cominco's Saskatchewan potash shafts. Ninth Commonwealth Mining and Metallurgical Congress. Mining and Petroleum Geology Section. Institution of Mining and Metallurgy. London. pp. 1-20

Klein, J. 1989. Shaft sinking by ground freezing in the coal-mining industry in the Federal Republic of Germany. Shaft Engineering Conference. 5-7 June. Institution of Mining and Metallurgy. Harrogate, England. pp 269-280

Neelands, A. R. 1926. The Thorne Colliery pit sinkings. pp. 1-43

Stoss, K. and Braun, B. 1983. Sinking a freeze shaft with installation of a water-tight, flexible lining. RETC Proceedings, Volume 1. pp. 513-532

Tunnicliffe, J. F. and Keeble, S. 1981. Shaft sinking at Selby. The Mining Engineer. August. pp. 69-79

Wild, W. M. and Forrest, W. 1981. The application of the freezing process to ten shafts and two drifts at the Selby Project. The Mining Engineer. June. pp. 895-904

Williams, A. and Auld, F. A. 2002. Boulby mine shaft lining design – second restoration. Trans. Instn Min. Metall. (Sect. A: Min. technol.), 111, January – April. The Institution of Mining and Metallurgy. pp. A13-A27

Zhang, Y., Liu, Z. and Duan, B. 2012. Achievements of China's coal mine construction in recent years. 3rd International Conference on Shaft Design and Construction. April. London. Tunnels and Tunnelling International. pp. 127-130