Forensics by Freezing

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ABSTRACT

Subsurface conditions in water bearing unconsolidated soils can often produce difficult construction situations for the installation of secant piles, slurry diaphragm walls and jet grouted impermeable zones. In certain isolated cases, ground freezing has been used to provide temporary earth support and/or groundwater control where these varying unpredicted conditions retard or even prevent construction. The concept of freezing these soils to the state of a strong, impermeable medium not only facilitates excavation, but also permits visual observation of the conditions that created the initial difficulties. This paper presents case histories where ground freezing was used as a remedial technique for slurry diaphragm walls, jet grouted base seals and secant pile excavation support. The paper evaluates the soil conditions and provides a forensic analysis of the cause of the complications that lead to the need to implement ground freezing.

INTRODUCTION

Artificial ground freezing is a method used to provide temporary earth support and ground water control for deep excavations, typically in water bearing unconsolidated soils, but occasionally in highly fractured rock. Freezing is accomplished by drilling and installing a series of subsurface refrigeration pipes along the perimeter of the proposed excavation. A refrigerated coolant is circulated through the frozen pipes, forming a frozen earth barrier. (see Figure 1).

There are different methods of drilling and installing the freeze pipes, as well as two primary methods of refrigeration. One of these methods is referred to as the direct expansion where a cryogenic liquid, such as liquid nitrogen, is pumped into the pipes to vaporize. The gas is then released into the atmosphere. This method is extremely expensive and typically used on small, emergency projects (Sopko, Khorshidi, McInnes, 2016). A more common method is a closed circulation system in which a primary refrigerant such anhydrous ammonia or R22 cools the circulating coolant in a heat exchanger.

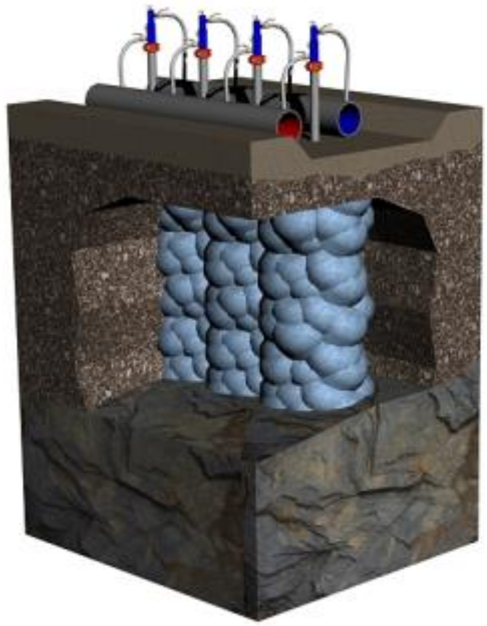

Figure 1. Schematic of a frozen earth barrier

The configuration of a typical closed system refrigeration pipe is similar to that presented. (see Figure 2). Figure 2 also illustrates the formation of the cylinders with time, leading to the full formation (see Figure 3). Ground freezing has several significant technical advantages

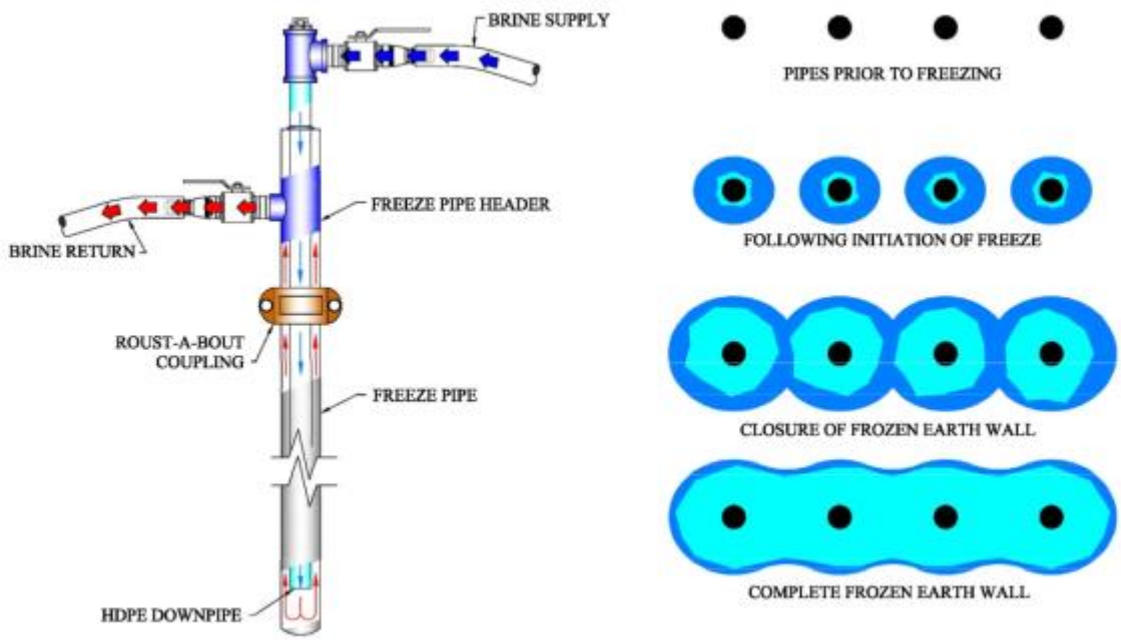

Figure 2. Schematic of a refrigeration (freeze) pipe and typical configuration

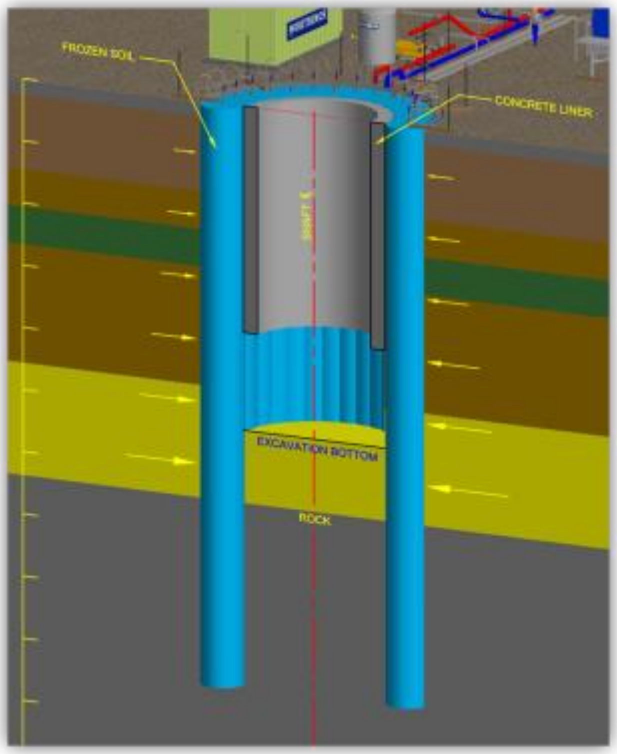

Figure 3. Typical cross section of a frozen shaft

when compared to other more conventional earth support and groundwater systems. Specifically:

1. Freezing can be used in relatively any type of soil formation;
2. Cobbles and boulders are typically not a factor as long as the proper drilling method is selected for the installation of the refrigeration pipes;
3. It can be used for shafts with depth in excess of 600 m; and
4. The unit cost of the frozen ground typically reduces as the depth of excavation increases.

Consequently, there are also disadvantages of freezing. Most notably, once the system is drilled and installed, it can take six to ten weeks of freezing to form the required structural thickness and temperature of the frozen ground. Additionally, it is typically more expensive than conventional methods.

The above statement was not meant to be critical of the conventional methods. Often times freezing is considered a last resort approach. In cases where other earth support and groundwater control methods have been unsuccessful, the disadvantages of the time requirement and expense of ground freezing are outweighed by the technical advantage.

This paper discusses certain cases where ground freezing was used after conventional methods were unable to provide a stable and safe excavation. Ground freezing not only affords the completion of the referenced projects; it also allows visual inspection of the problems encountered prior to the freezing. This paper is not intended to critique other methods, but rather to provide a forensic approach as to what can, and sometimes does happen in the variable and uncertain world of the underground.

CASE HISTORIES

The following represent two projects where ground freezing was not initially selected as the preferred method of temporary excavation support and groundwater control, due primarily to the schedule and associated costs. Nevertheless, ground freezing was ultimately used to complete the projects and provide the opportunity to inspect the complications with the initial approaches.

Bushwick Shaft 20B- New York, New York

Construction of a 13m diameter shaft through approximately 100m of water bearing, unconsolidated soils and an additional 100m of bedrock was attempted using the slurry diaphragm wall method with a combination of deep wells. Ground freezing was initially considered; however, in 1990, New York City did not permit the use of freezing without the installation of a secondary support system such as steel ribs and wood lagging or liner plates. This “belt and suspenders” approach was too expensive and freeze was eliminated as a cost effective approach.

The slurry wall was constructed to a depth of 59m (see Figure 4). The initial plan was to dewater the Raritan sand with deep wells and continue mining with steel ribs and wood lagging into the competent bedrock. Ground freezing from within the shaft was also considered as a method to complete the excavation.

The slurry wall was constructed with a series of seven panels using the sequence illustrated (see Figure 5). During the initial excavation a small gap was observed between panels 3 and 5 and was later repaired. The excavation resumed to a depth of 36m where another intrusion occurred between the same panels. Once again repairs were made, only to have another occurrence at 38m. This third breach was repaired before resuming the excavation.

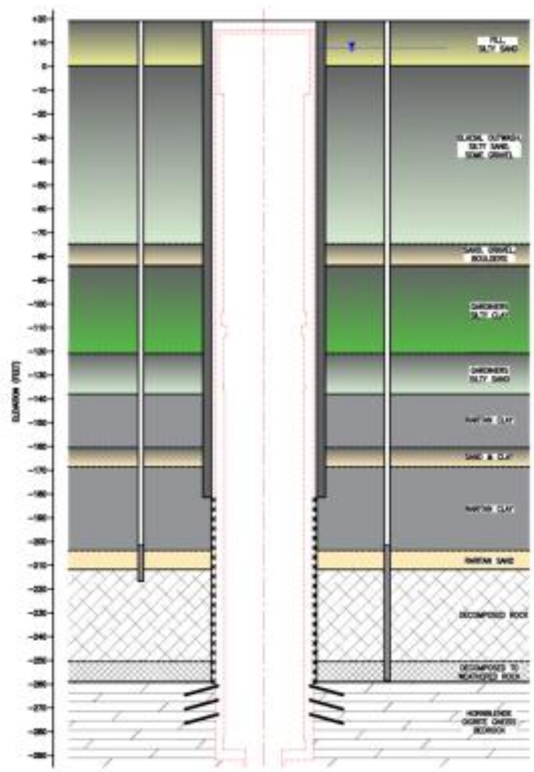

Figure 4. Cross section of proposed slurry wall construction

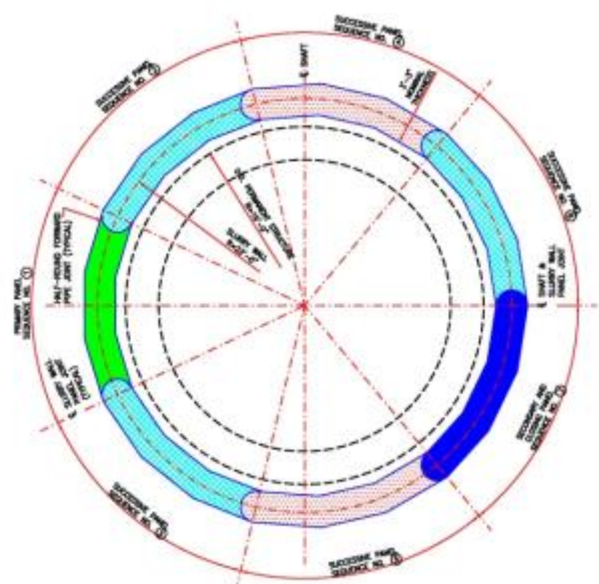

Figure 5. Panel construction sequence

The shaft was flooded and excavation suspended while a grouting program was implemented in an attempt to seal the joints between the slurry wall panels. Cement-bentonite grout was injected repeatedly through tubes à manchettes that were drilled and installed in the area of the leaking joints.

As the excavation was initiated, a major blow-in occurred bringing several hundred cubic meters of material. It was estimated that approximately 700m^3 of silty fine sand had flowed into the excavation over a 12-hour period. The ground loss was significant enough that ground settlement was observed at the surface and damage was reported to residential foundations near the shaft.

After it was determined that the slurry wall could not be repaired, ground freezing was selected as the most technically appropriate method to complete the shaft. The initial design computation indicated the combination of depth and diameter, as well the mechanical properties of the soils would result in the most highly stressed frozen earth structure (at that time) in New York City.

The complications of freezing the creep susceptible Raritan Clay, frost pressures generated against an existing, damaged slurry required additional analysis. Primary frost effects are those caused by the immediate expansion of water as it freezes and increases in volume approximately nine percent. Secondary frost effects are those created as freezing water is drawn toward the frozen/unfrozen soil interface, which eventually freezing and creates ice lenses that can generate even greater forces against the slurry wall. Based on the evaluation of the underlying soils, it was determined that only primary frost effects would occur. Analysis indicated an additional 700 kPa pressure against the slurry wall.

Review of the slurry wall design indicated that while it was capable of withstanding these additional pressures as designed, any misalignment of panels could lead to unbalanced loading and structural damage. The frozen earth structure was designed to support all earth and hydrostatic loading, essentially assuming the slurry wall did not exist. However, there was concern that damaged panels could break apart and fall into the shaft, creating an extremely dangerous situation. For this reason, additional bracing was installed during the pumping down phase.

After approximately six weeks of freezing, the waste from inside the slurry wall was pumped out, and excavation resumed. The freezing eliminated any groundwater infiltration and bottom instability. As the dry excavation progressed, it was possible to closely inspect the slurry panels in their entirety.

This inspection revealed that there was an approximate 1.5cm gap between two panels. The gap was basically filled with the cement-bentonite grout. However, at a depth of 40m, it was observed that the gap was filled with frozen soil, indicating that the hydrostatic pressures blew out the grout that was temporarily providing a seal.

Access Shaft 3-Buenos Aires, Argentina

The Sistema de Potabilización Área Norte project (Northern Area Purification System) was a major expansion of the potable water system in Buenos Aires Province, Argentina. The project is designed to transport and purify water from the Paraná River to five communities in the northern zone of the province.

Five access shafts and eight ventilation shafts were installed along the 15km tunnel alignment. The five shafts consisted of:

- One central shaft in the center of the tunnel alignment
- Two retrieval shafts
- Two intermediate shafts

The intermediate shafts were excavated prior to tunnel operations with the plan to then install the final shaft lining after tunnel completions. The shafts were constructed using slurry diaphragm wall with jet grouted bottom seals. Additionally, soils at the tunnel entrances and exits to the shafts were improved using jet grouting.

Access Shaft 3 (AS-3) was located between the tunnel launching shaft and the water treatment plant, which was also part of the construction contract. Construction of AS-3 was attempted using the slurry wall augmented with a jet grout bottom seal. The soil profile at the site, as well as the excavation support system is presented below (see Figure 6). The groundwater level at this site was only 1.5m below the ground surface resulting in relatively high hydrostatic forces against the panels and also the excavation base.

The individual slurry wall panels were 0.8m thick by 2.5m long and extended to a depth of 29.7m. The steel reinforced panels formed a 10.8 m interior diameter temporary structure. The jet grouted bottom seal as shown in Figure 5 was comprised of columns that were 3.5m long and had an approximate diameter of 1.2m. The tunnel boring machine (TBM) entrance and exit areas of the shaft consisted of the same 1.2m diameter jet grout columns forming blocks of 10m by 10m with a height of 5m.

The initial excavation proceeded as planned to a depth of 10.5m. At that point an inflow of water was observed that continued to increase at an alarming rate. When flowing soil was observed, the contractor immediately flooded the shaft. Further evaluation concluded that there were gaps between some of the slurry wall panels.

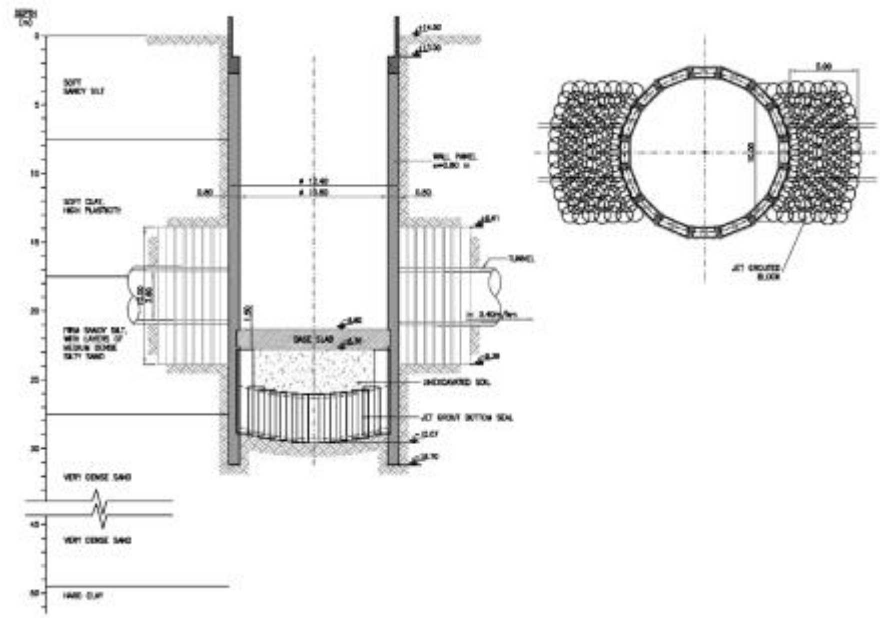

Figure 6. Proposed slurry wall with jet grouting

During the next several months, excavation was attempted using the following remedial techniques:

- Grouting with cement-bentonite through tremie pipes adjacent to known leak locations
- Drilling and installation of tubes à manchettes for additional cement-bentonite grouting
- Jet grouting around the perimeter of the entire shaft
- Dewatering with deep wells to reduce hydrostatic pressure
- Using divers to place formwork and injecting grout from inside the shaft

These attempts were unsuccessful as numerous joints around the perimeter at depths from approximately 13m to 23m experienced groundwater infiltration. This was in the layer of firm sandy silt with layers of medium dense silty sand. After continued attempts, the shaft experienced a major failure when soil flowed into the shaft during an overnight period. It was estimated that approximately 2.4m of soil accumulated in the bottom of the shaft.

In order to keep the tunnel mining on track, concrete was tremied into the shaft to the elevation just below the tunnel invert. Even though the slurry wall panels were still leaking, the contractor was able to break out the entrance and exit of the TBM from inside the shaft. The jet grouted mass prevented soil and water inflows. Once these openings were completed, an additional 7.2m of lean mix was poured into the shaft, (two times the TBM diameter) to permit continuation of tunneling operations without completing the shaft.

After the tunneling had been completed it was necessary to construct the shaft. Ground freezing was selected as the most technically appropriate method to not only seal the leaks in the slurry wall, but also to penetrate deep enough into an impermeable stratum to ensure bottom stability.

A configuration of refrigeration pipes was drilled and installed from the ground surface (see Figure 7). Note that angled pipes were necessary to ensure the zone below the tunnel was

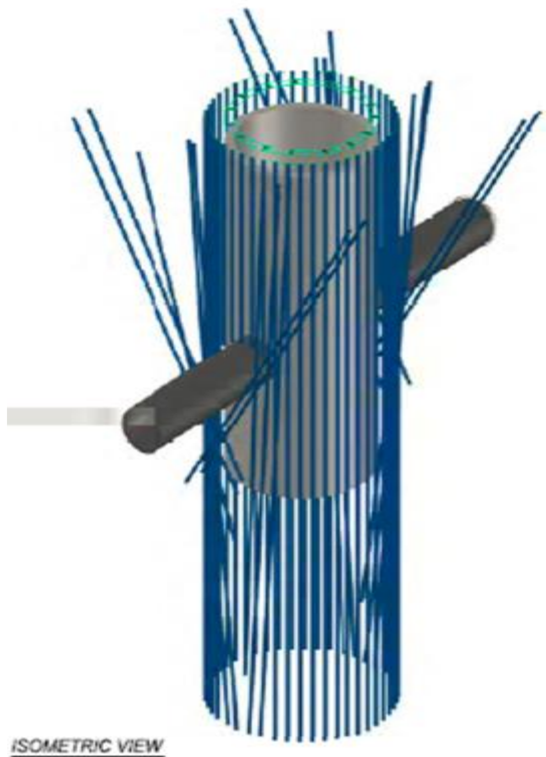

Figure 7. Refrigeration pipe configuration

frozen. Ground freezing commenced and after approximately eight weeks of freezing the flooded shaft was pumped down. During this pump down it was possible to evaluate the condition of the slurry wall. The photos show significant gaps in the panel joints, filled with grout from the several remedial attempts prior to freezing (see Figure 8). During the design of the freezing system there was concern that the pressures generated by the expansion of groundwater during phase change would exert forces on the slurry wall and result in damage. This was not observed.

Figure 8. Inspection of slurry wall after pump down

CONCLUSION

Two case histories of projects where ground freezing was used to remediate slurry walls have be documented. Encapsulating the slurry walls in ice enabled the contractors to further understand the soil conditions that complicated the slurry wall construction

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