Ground Freezing for Two Frozen Shafts at the Bergen Point Outfall Tunnel

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ABSTRACT: Construction of a 9700m, 180cm diameter effluent pipeline required tunnelling from an existing sewage treatment plant to a barrier island outfall structure. Construction of the tunnel required a launching shaft at the plant and a receiving shaft at the barrier island. Artificial ground freezing was specified as the method to provide temporary earth support and groundwater control at the launching shaft and selected by the contractor for the receiving shaft. Design of the ground freezing system was complicated by existence of lateral groundwater flow and the need to freeze the base of the shaft to provide bottom stability. Frozen ground laboratory tests were conducted to evaluate the strength and deformation characteristics of the frozen mass to design a temporary liner needed for tunnelling operations. This paper details the design process used, including a heat transfer and groundwater flow FEM model to address the specified lateral groundwater flow as well as the stress analysis using the frozen soil laboratory test data. Discussion on the approach to create a frozen bottom plug as well as insulation methods to not freeze the interior of the shaft above this plug is included.

KEYWORDS: Tunnelling, Ground freezing, Earth support, Groundwater control, Bottom stability

1. PROJECT BACKGROUND

The construction of a 9700m, 180cm diameter effluent pipe required a launching shaft at the existing sewage treatment plant and a receiving shaft at a barrier island adjacent to the Atlantic Ocean on Long Island, New York. The contract requirements specified ground freezing at the launching shaft and indicated a preference for freezing at the receiving shaft. The dimensions of both shafts are shown in Figure 1, while the generalized soil profiles are shown in Figure 2. The literature is somewhat saturated with articles on using ground freezing to provide temporary earth support and groundwater control for shafts as simple as these; however, this project had noteworthy aspects. Specifically:

- The geotechnical baseline report indicated that the ground freezing system must be designed to accommodate a groundwater velocity of 0.91 m/day.
- There was no impermeable stratum at the base of the excavation requiring a frozen bottom to provide hydraulic stability.
- A frozen "break-in" zone would be constructed at the receiving shaft for TBM entry.

These issues are addressed in this paper, showing modifications necessary to conventional frozen earth cofferdam design.

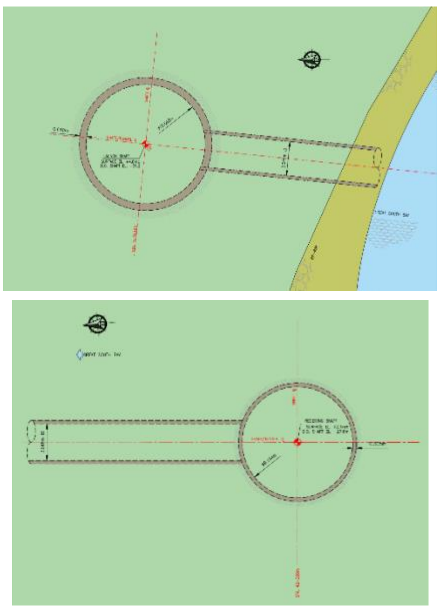

Figure 1. Dimensions of launch (top) and receiving shafts (bottom)

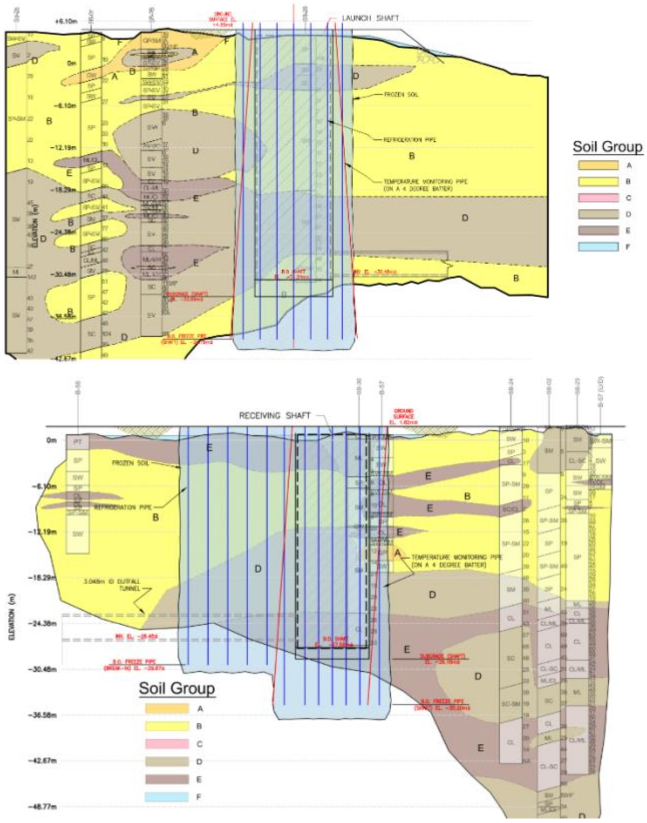

Figure 2. Soil profiles of launch (top) and receiving shafts (bottom)

2. GROUND FREEZING SYSTEM

The ground freezing system for each shaft consisted of a series of 114.3mm diameter steel pipes around the perimeter of the excavation shown in Figure 3. The proposed depths of the pipes were 44.8m at the launching shaft and 38.7m at the receiving shaft.

Prior to evaluating the groundwater flow and bottom stability, an analysis was conducted to evaluate the structural stability of the frozen wall. After several iterations of frozen earth wall thickness, it was determined that a 1.82m wall would be required. However, the specifications required that the frozen wall thickness should be 3.5m. An analysis was conducted using PLAXIS as shown in Figure 4. After review of the analysis, it was agreed that the 1.82m wall would be used.

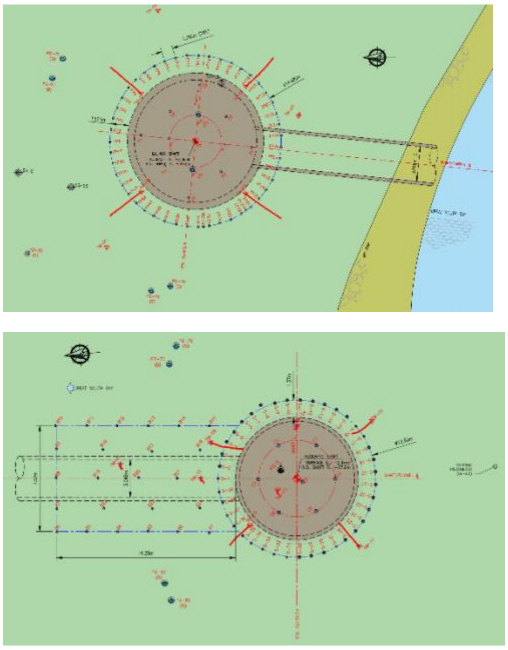

Figure 3. Series of steel pipes around perimeter of excavations

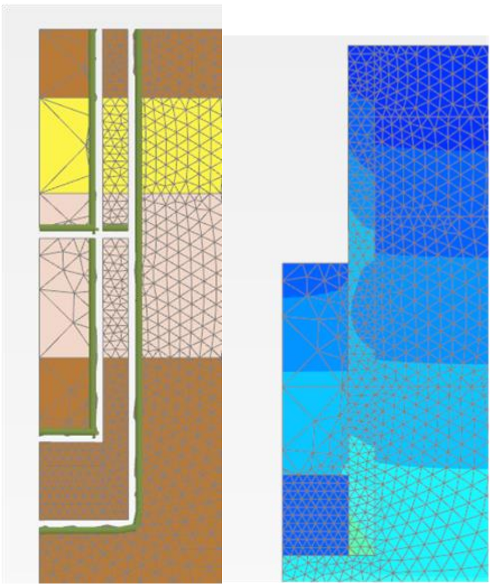

Figure 4. Finite Element Mesh and Stress Contours

3. LATERAL GROUNDWATER VELOCITY

The frozen earth wall would be formed with a refrigeration pipe spacing around the perimeter of approximately 1.0m. Prior to installation however, it was necessary to evaluate the effects of a 0.91m/day groundwater velocity. Lateral groundwater flow will introduce heat into the ground freezing system and in some cases can retard or even prevent the formation of a frozen earth wall. There are two approaches to evaluating the groundwater effects. One approach is to use a coupled finite element analysis that used both a thermal and groundwater flow concurrently. This is used in more complex pipe configurations, particularly where there are field measurements indicating groundwater flow.

On this particular project, while the specifications indicated that the project be designed to accommodate the 0.91m/day velocity, there was no evidence in borings or piezometer data to indicate that a sufficient gradient and high permeability soils existed to create groundwater flow of this magnitude. A subsequent geotechnical investigation conducted by the ground freezing contractor confirmed this.

A simpler approach was used as proposed by Andersland & Ladanyi (2004) to compute the critical groundwater velocity was used as shown in Equation 1. The critical ground velocity is the velocity above which freezing will not occur based on the following criteria:

1. Circulating coolant temperature -30 °C
2. Groundwater temperature 13 and 15 °C
3. Refrigeration pipe radius 57.1mm
4. Refrigeration pipe spacing (varied)

$$v_c = \frac{k_f}{4S\ln\frac{S}{4r_0}}\frac{V_s}{V_0} \qquad (1)$$

v_c: critical groundwater velocity
k_f: constant: (3.4 W/m °C)
V_s: brine temperature: -30 °C
V_0: groundwater temperature: 13 °C
r_0: refrigeration pipe radius: 57.1mm
S: refrigeration pipe spacing (variable)

Using the equation, the curves were developed, as shown in Figure 5. With a refrigeration pipe spacing of 1m (3.29 ft), it can be observed that the critical groundwater velocity is well above the required 3.0 ft (0.91m) per day. With this confirmation, the design proceeded to the next phase that included a frozen base to provide hydraulic stability.

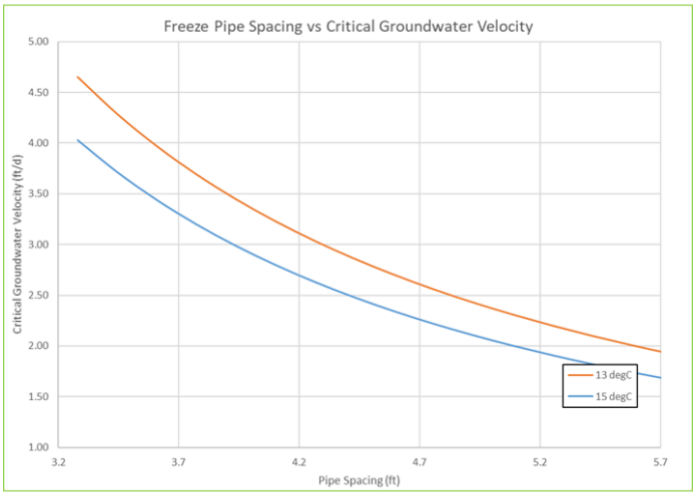

Figure 5. Freeze Pipe Spacing vs. Critical Groundwater Velocity

4. HYDRAULIC BASE STABILITY

Figure 2 indicates the presence of mostly coarse-grained sand and silty sand at the inverts of both shafts. In ground freezing, it is often possible to drill and install the refrigeration pipes deeper into an impermeable material at a relatively lower price than with a diaphragm wall or using a form of ground improvement. As previously stated, the ground freezing contractor conducted additional exploratory borings. These borings were to verify the potential groundwater gradient, procure samples for frozen soil laboratory testing, and drill deeper to identify a potentially impervious stratum to terminate the frozen earth structure.

When no impermeable stratum was located, design began on a frozen earth base, as shown in Figure 3. The spacing of the refrigeration pipes within the frozen cofferdam was determined by completing thermal models using different spacing and geometric designs.

Two separate models were used in the final design. The first model did not have the interior pipes as it was used to evaluate the thickness of the shaft support. This model is presented in Figure 6.

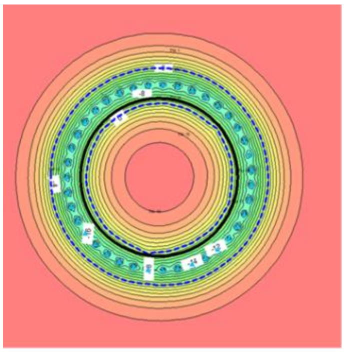

Figure 6. Frozen Earth Structure at 42 Days

After determining that the frozen earth structure thickness of 1.82m would be achieved in 42 days, an additional model was completed that included the frozen zone at the base, as shown in Figure 7.

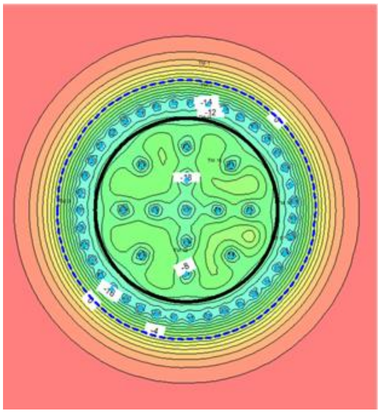

Figure 7. Frozen Earth Structure at 42 Days with Frozen Base

The excavation plan included disconnecting the interior pipes from the refrigeration system and cutting the pipes as the excavation progressed. Subsequent thermal models were run that de-activated the interior pipes after 42 days. These models showed that the circular array of pipes along the perimeter would maintain the frozen center. The models actually showed that the base continued to get colder with time.

The depth of the pipes that form the thickness of the frozen base would require a three-dimensional heat transfer model. Another option was to rely on the ground freezing contractor's extensive experience with bottom stability. Relying on this experience, an approximately 10m base plug was selected. Sufficient thickness is required to compensate for any thawing from the bottom that the two-dimensional section model would not indicate.

5. EXCAVATION

Even though the interior pipes would be disconnected, the design, as shown, would freeze the entire depth of excavation. Excavating through frozen ground is considerably more complex than unfrozen ground. In the Launching Shaft, a method of using a PVC sleeve and low thermal conductivity grout was used to provide insulation above the base plug. The excavation was somewhat difficult and slow.

A different insulation method, as shown in Figure 8 was used on the Receiving shaft and proved to be more effective in limiting the growth of frozen soil around each refrigeration pipe.

Figure 8. Application of Polyurethane Insulation

The project specifications required that a 0.30m thick shotcrete lining be installed as the excavation progressed. There was concern that it would be difficult to place this lining and ensure it did not slip as the excavation progressed. The ground freezing contractor suggested that the excavation proceed to the invert relying only the support of the frozen earth covered with polyurethane insulation. The ground freezing contractor assumed all risk for a stable excavation.

Photographs of the excavation are shown in Figures 9 and 10.

Figure 9. Excavation of Launching Shaft

Figure 10. Completed Excavation with Abandoned Interior Pipes

After completing the Launch shaft excavation, a mud slab was poured, followed by the reinforced concrete bottom. The final lining was applied using shotcrete from the bottom up.

6. RECEIVING SHAFT BREAK-IN

While planning the ground freezing system at the Receiving Shaft, the tunnel contractor selected ground freezing as the method to provide a stable TBM break-in. Ground freezing provided economic savings over other methods since the equipment was already on-site, and the frozen mass could be connected to the existing system.

A thermal model was completed to evaluate the refrigeration pipe spacing in the frozen mass as shown in Figure 11.

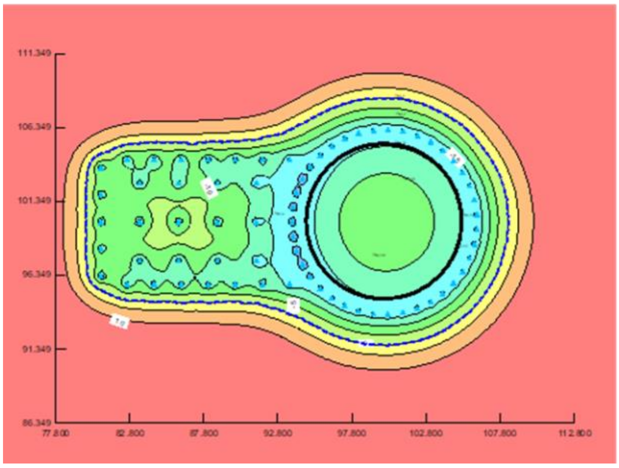

Figure 11. Thermal Model of the TBM Break-in

The concept of the frozen earth break-in relied on a sequence of tasks to ensure that the TBM could enter the shaft without groundwater intrusion. In these highly pervious soils, a relatively small leak could increase quickly as groundwater flowed into the shaft and melted and eroded the frozen soil in within the mass. After the formation of the frozen mass, the sequence of tasks is described:

1. As the TBM approaches each row of refrigeration pipes, evacuate the calcium chloride coolant from each individual pipe.
2. Heat each pipe to break the strong ad-freeze bond between the soil and the pipe steel.
3. Pull each pipe to an elevation directly above the crown of the tunnel.
4. Re-connect the pipe to the coolant distribution system.
5. Continuously mine into the frozen mass and install segmental lining.
6. Grout the annulus between each segment and the frozen mass.

Grouting the annulus between the segments and the frozen soil is the most important task in the sequence. It is imperative that groundwater cannot flow through the annulus and into the shaft opening. In this case, a urethane was used successfully.

The break-in proceeded on schedule as shown in Figure 12. The TBM was then dismantled and removed from the Receiving Shaft. The freezing system remained operational as the riser pipe was installed and connected to diffuser. The shaft was backfilled without the installation of any temporary lining.

Figure 12. TBM Break-in

7. SUMMARY AND CONCLUSIONS

As previously stated, this was a relatively routine ground freezing project, with the exceptions of the lateral groundwater flow (that was nonexistent), the need for bottom stability, and the TBM break-in. There were other components of the project that should also be considered when evaluating freezing on subsequent projects.

The specified shotcrete liner was required to mitigate any creep deformation that is sometimes associated with leaving a frozen shaft excavated for long periods of time. Creep deformation is a function of the soil type, temperature, stress state, and time. As previously noted, the ground freezing contractor conducted its own frozen soil laboratory test to evaluate creep behavior and concluded that there was no need to install a temporary liner. Observations of both shafts, particularly the receiving shaft was open for over one year, there was measurable creep deformation.

The Receiving Shaft on the barrier island presented a logistical problem. Not only was there no commercial power requiring generators, but there was also no water source to provide cooling water for the evaporative condenser. Water had to be delivered to the site daily. However, during the colder months, the condensers were air-cooled.

In summary, this project provided unique opportunities to complete two shafts in very permeable soils. The concept of using freezing for both the excavation support and bottom stability eliminated the need for multiple technologies. The use of freezing on both shafts and the TBM break-in resulted in dry, safe, and successful excavations.

8. REFERENCES

Andersland, O.B. & Ladanyi, B. 2004. Frozen ground engineering. Hoboken: John Wiley & Sons.

9. AUTHOR & REVIEWER COMMENTS

Remark: Word count is a little low, have space to add additional details. Although, this is compensated by figures and clear narrative.

Author comment: We believe our paper length is supplemented by the figures and narrative we have.

Remark. Check the spelling of sewerage treatment plant.

Author comment: We have corrected this spelling in the various instances to now say ‘sewage treatment plant’.

Remark: Missing numbers in the paragraph of the 2nd heading GROUND FREEZING SYSTEM.

Author comment: We have inserted the missing numbers as requested.