Ground Freezing to Repair Leaks in a Slurry Wall Shaft

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PROJECT OVERVIEW

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 aim of the project was to transport and purify raw water from the Paraná River to provide potable water for five communities in the northern part of the province, benefitting up to two million inhabitants. The project was constructed by a joint venture of four South American contractors ("the JV"), and consisted of the following key components:

- **Treatment Plant**: A 16 hectare area was cleared for the construction of a treatment plant to purify 900,000 m^3/day of raw water from the Paraná River and distribute it to the surrounding communities.
- **Bored Tunnel**: Nearly 15 km of 3.6 m inner diameter tunnel, ranging from 18 to 22 m below grade, was bored with two EPB tunnel boring machines to draw the raw water from the river. The TBMs started from a central launch shaft and proceeded in opposite directions: *Cristina* advanced northbound to the Paraná River Intake System, and *Liliana* advanced southbound to the new treatment plant.
- **Access & Ventilation Shafts**: Five access shafts and eight ventilation shafts were installed along the length of the tunnel. The access shafts were designed to provide entry points for inspection and maintenance of the final tunnel. The five shafts consisted of: one central launch shaft in the middle of the tunnel alignment, one retrieval shaft at each end of the tunnel (Intake and Treatment Plant, respectively), and two intermediate shafts. The intermediate shafts were installed before the TBM passed, with a final liner to be installed afterwards. Access Shaft 3, the intermediate shaft located between the launch shaft and the treatment plant, experienced persistent leaks during initial excavation attempts.

ACCESS SHAFT 3

The soil near Access Shaft 3 (Cámara de Acceso 3, or CA3) generally consisted of soft to medium sandy silts and clays from EL +14.5 m to EL -13 m, underlain by very dense sand to EL -34 m. A hard clay layer was encountered beneath EL -34 m. Groundwater was encountered at EL +13.2 m (1 to 1.5 m below grade).

The temporary liner for CA3 was comprised of 0.8 m thick by 2.5 m long by 29.7 m deep steel-reinforced slurry panels that formed a 10.8 m interior diameter structure, as shown in Figure 1. Waterstops were not used between the panels. A bottom seal of jet grout columns, each 3.5 m tall with a nominal diameter of 1.2 m, was designed to provide base stability by resisting hydrostatic forces due to the high water table. Jet grouted blocks measuring 10 m high by 10 m wide by 5 m thick were formed using 1.2 m diameter columns around the tunnel break-in and break-out areas to provide stabilization for TBM passage.

Initial excavation began in October 2012 and proceeded without incident for the first week. At a depth of 10.5 m, there was an inflow of water at a joint between wall panels. The leak increased rapidly and began to carry soil into the shaft, so the JV flooded the shaft to equalize the internal and external pressures and reduce further inflows until the situation could be assessed.

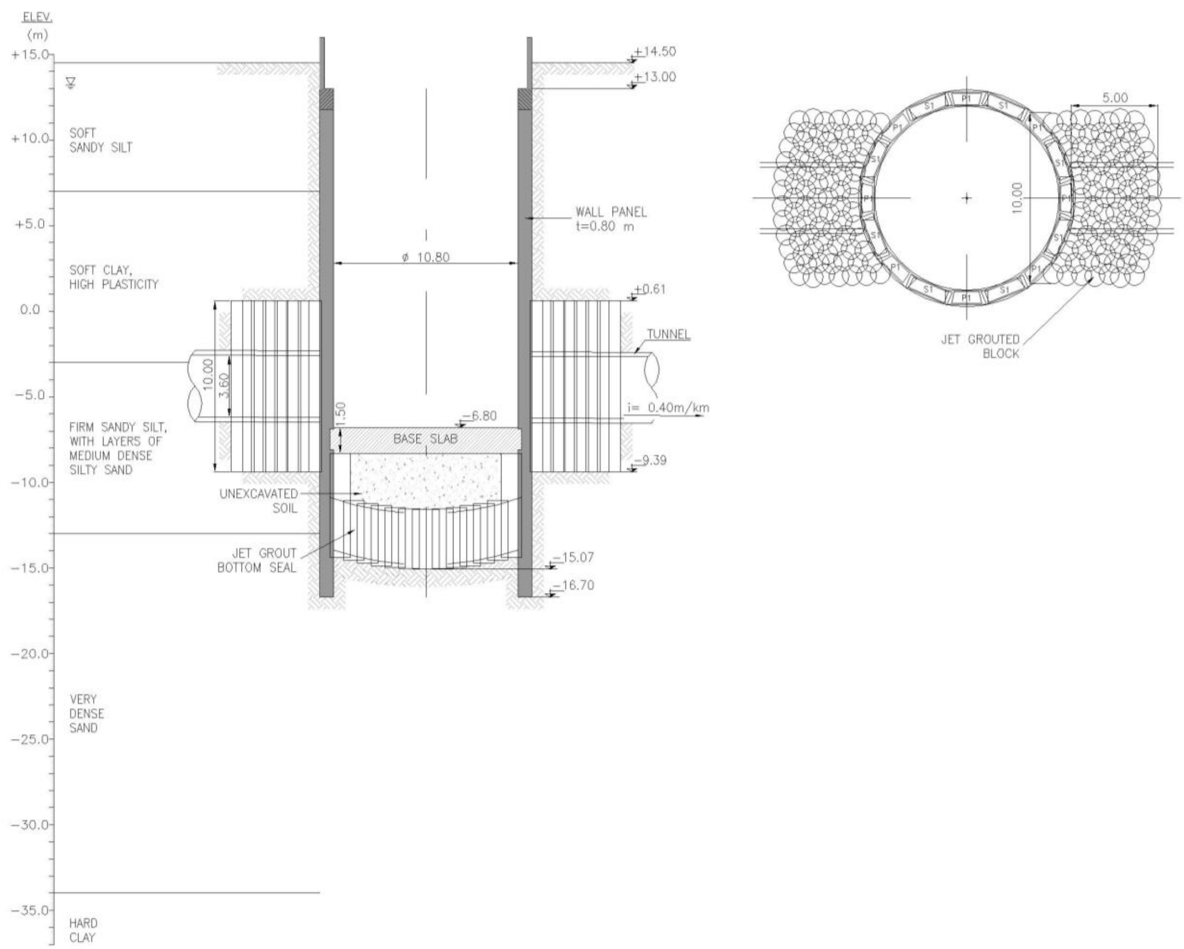

Figure 1. Shaft section and plan showing soil strata and construction details

Over the next four months, the JV attempted several different methods to repair the leak: tremie grouting, tube-a-manchette grouting and jet grouting behind known leak locations; jet grouting around the entire exterior perimeter of the shaft; dewatering with deep wells to reduce hydrostatic pressure; and using divers to place formwork and inject grout from inside the flooded shaft. Each was unsuccessful and the JV had to flood the shaft several more times as new leaks were encountered in seven different joints at a range of heights from EL +2.5 m to EL -8.5 m. The volume of leaks was not measured with close accuracy, but in January 2013 the water carried such a volume of soil that it accumulated to a depth of 2.4 m in the shaft over the course of the night.

By early 2013, progress of the southbound TBM *Liliana* was severely hampered by the delays at CA3. In February, the JV tremie-poured concrete into the shaft to the level of the tunnel invert, then used an excavator with a hydraulic breaker to create openings in the slurry wall for the TBM break-in and break-out; the jet-grouted blocks behind the openings provided isolation from the surrounding soil. The leaks persisted and precluded the construction of the final cast-in-place liner, but a series of trenches and sumps at the base of the shaft controlled the water sufficiently to allow demolition work to proceed.

When the openings were complete, the JV backfilled the shaft to approximately 7.2 m above the tunnel crown (two times the tunnel diameter) in order to allow tunneling to continue. After the TBM passed, the JV contacted a specialty geotechnical subcontractor to provide a solution for the shaft's persistent leaks.

GROUND FREEZING DESIGN & INSTALLATION

The geotechnical subcontractor proposed the use of artificial ground freezing: the extraction of heat from the ground until the pore water in the soil freezes. This technique creates an impermeable, rigid mass of in-situ frozen soil.

To chill the soil, metal freeze pipes are installed in the ground at regular spacing. Calcium chloride brine, chilled by mobile refrigeration plants, is circulated through the pipes; the warm soil transfers heat to the cold brine, and the soil is cooled incrementally.

Proposed Layout

The system required an array of freeze pipes to freeze the soil around the shaft and isolate the shaft interior from the groundwater to cut off the source of the leaks. The frozen wall was designed to provide an independent water cutoff (the slurry wall and jet grouted base were disregarded). The preliminary design called for 68 freeze pipes: 48 vertical pipes at 1 m spacing placed 1 m outside the exterior perimeter of the shaft, and 20 angled pipes to cradle underneath the tunnel on either side of the shaft. The 10 vertical pipes above the break-in and break-out locations were installed to the top of the tunnel, approximately 18 m deep. The other 38 vertical pipes were installed approximately 55 m deep, extending several meters into the hard clay layer below EL -34 m. The clay provided an impermeable stratum at the bottom of the frozen cylinder to prevent water recharge from below. Additional pipes for temperature monitors and piezometers were also installed to provide data on soil temperature and groundwater levels. Figure 2 shows a rendering of the proposed freeze pipe layout.

In addition to surface pipes, two circuits of contact cooling tubes were proposed for inside the tunnel. These tubes were mounted onto the surface of the concrete liner to chill the concrete on either side of the shaft; they were intended to prevent the warm tunnel from supplying heat to the ground freezing system.

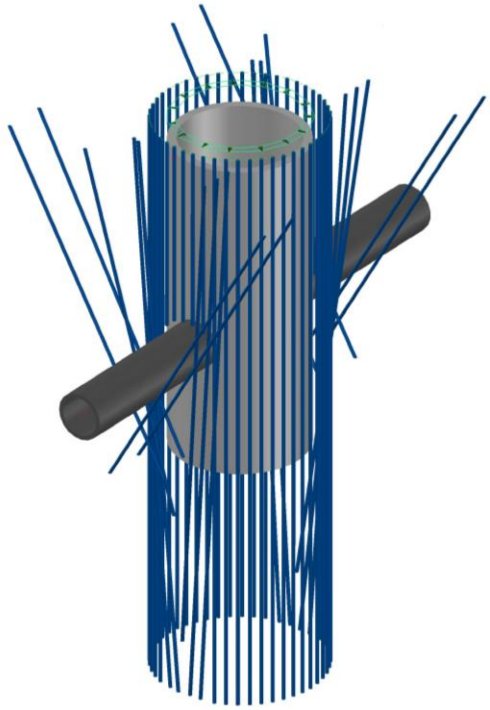

Figure 2. Proposed freeze pipe layout

Structural Design

The structural engineers were concerned about the stresses on the shaft and tunnel due to the volumetric expansion of frozen soil. Plaxis 3D was used to determine that the additional pressure on the shaft wall and the tunnel could be as high as 520 kPa, with the largest stresses at the intersection of the tunnel and shaft.

With this data, the structural engineers designed concrete rings to reinforce the tunnel liner; two 25 cm thick rings extended 4.5 m in each direction out from the exterior of the shaft walls, roughly corresponding to the area encompassed by the jet grouted blocks. The rings were intended for temporary use and later removal, but were eventually left in place due to the need for structural support during ground thaw.

The engineers also designed masonry plug walls to be installed upstream and downstream of the shaft to protect the tunnel in case of shaft failure.

Thermal Design

To estimate the refrigeration energy and time required to form the proposed frozen wall, the ground freezing subcontrator performed a thermal design using the finite-element analysis program Temp/W. Because the wall was needed only for water cutoff and not for direct earth support, the target soil temperatures were not as stringent as for a conventional structural frozen wall.

The soil parameters for the thermal design were based on the sandy silt layer, assumed to be the least conducive to freezing. Additionally, the freeze pipe layout was modeled at the area of greatest concern: the tunnel invert elevation, where the distance between angled freeze pipes was largest. The

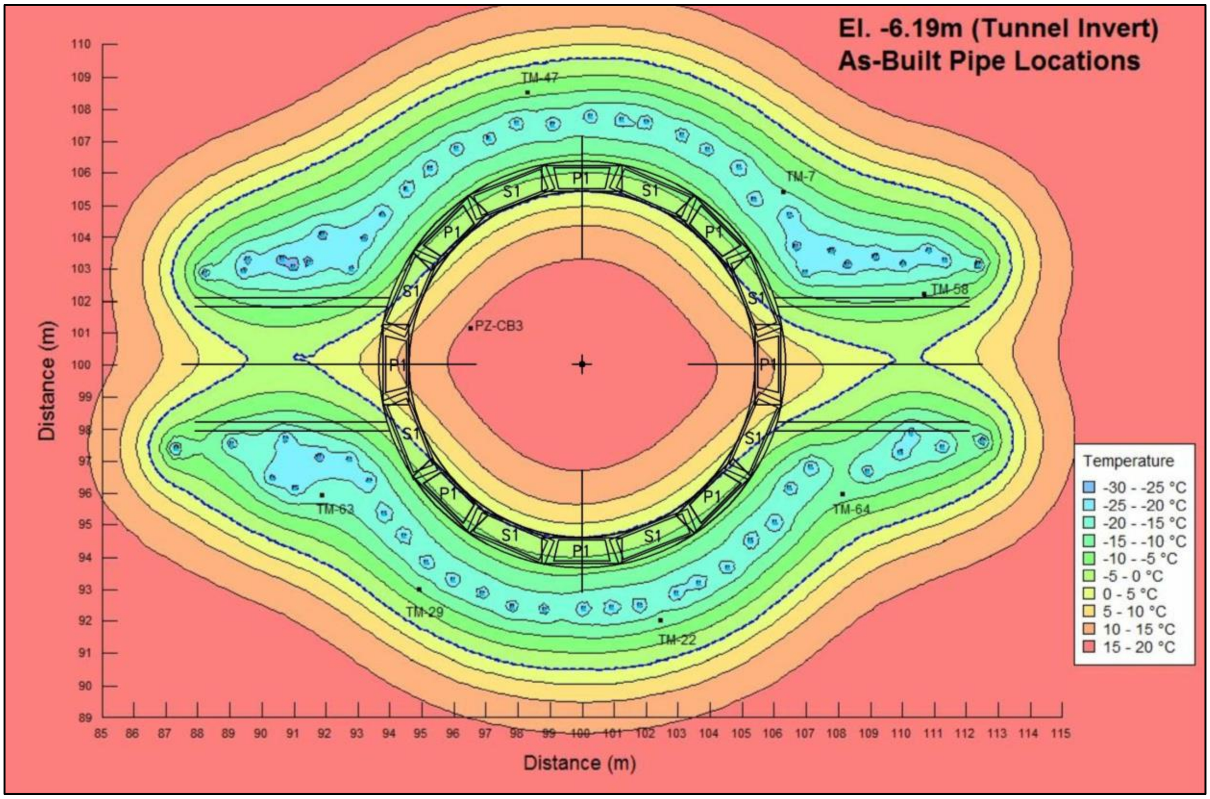

Figure 3. As-built Temp/W model contour plot with CA3 slurry wall superimposed. Temperature monitoring pipes are identified as TM-#.

design locations of the pipes were used initially; the analysis was repeated using as-built freeze pipe locations after installation. Figure 3 shows the thermal contour plot of the as-built Temp/W model.

The thermal analysis suggested that closure of the frozen wall would be achieved after approximately 63 days of freezing. The final portions of the frozen wall to close would be the areas immediately below the tunnel invert. The area of frozen soil is represented within the dashed blue contour indicating the 0° C isotherm.

System Installation

Freeze pipes and temperature monitors were installed by rotary drilling methods with a track-mounted core drill using bentonite mud as a drilling fluid. Once the holes were drilled to final depth, 114.3 mm diameter steel pipe was inserted into the borehole in 12 m sections and butt welded; an end cap was welded to the first segment in the ground. After installation, each pipe was pressure-tested to 150% of working pressure to ensure brine would not leak into the surrounding ground. The pipes were surveyed with an inclinometer to determine deviation from design; due to drilling tolerances, 73 pipes were installed rather than the design quantity of 68 pipes.

After drilling was completed, the brine circulation system was installed. The system consisted of the following components:

- **Refrigeration plants:** Two mobile plants (one 400 HP, one 300 HP) chilled the brine to a temperature of -25° to -30°C. Due to the incompatibility of American motors with the Argentine power grid, electric power was supplied by diesel generators.
- **Centrifugal pumps**: Two 50 HP pumps, connected in parallel, circulated brine through the piping and plants.
- **Header piping:** Insulated steel supply & return piping delivered brine through each freeze pipe and back to the plants.
- **Drop tubes:** Polyethylene tubes were inserted to the bottom of each pipe; brine flowed down each tube and returned through the annular space between the tube and the steel freeze pipe.
- **Tunnel cooling circuits:** Rectangular steel tubes were mounted directly on the tunnel liner rings. A pipe was drilled through the top of the tunnel from the interior of the shaft to connect the circuits to brine supply and return piping.

Figure 4 shows an aerial view of the system layout. Two rings of black insulated header piping surround the shaft: one ring supplies cold brine to the freeze pipes, the other returns warmer brine to the refrigeration plants.

Figure 4. Aerial view of the ground freezing system

Instrumentation

An instrumentation and data acquisition system was installed to monitor the ground freezing progress. The system included sensors for brine flow, temperature, and pressure; ambient temperature; soil temperature; and piezometer level.

Temperature monitoring pipes were installed around the shaft at varying distances from the frozen wall. A sensor string was installed in each monitoring pipe, with sensors spaced equally from the bottom to the top of the frozen wall.

The sensors were connected to a centrally located control panel and desktop computer for real-time monitoring and data-logging. The instrumentation system was activated one week prior to the start of freezing to gather baseline data for comparative purposes.

SYSTEM OPERATION

From September 10, 2014 until February 4, 2015, the plants operated 24 hours per day to freeze the soil around Access Shaft 3.

Progress of the frozen wall growth was monitored through daily analysis of the temperature data. The plots in Figures 5, 6 and 7 are each shown 64 days after freezing commenced. The soil cooled at different rates according to the following variables:

1. **Soil type:** As seen in Figure 5, sensors in the granular soil cooled more quickly than those in fine-grained silt and clay layers. Because silica and quartz have much lower heat capacities than water, soil with higher water content takes longer to freeze.

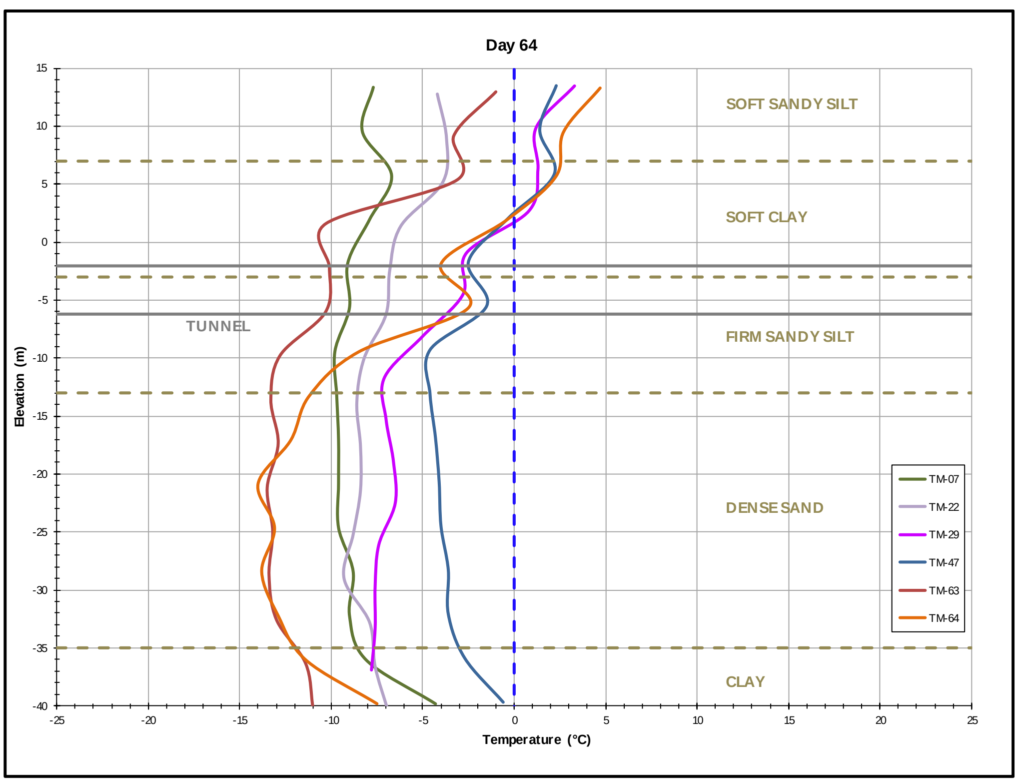

Figure 5. Elevation vs. Temperature

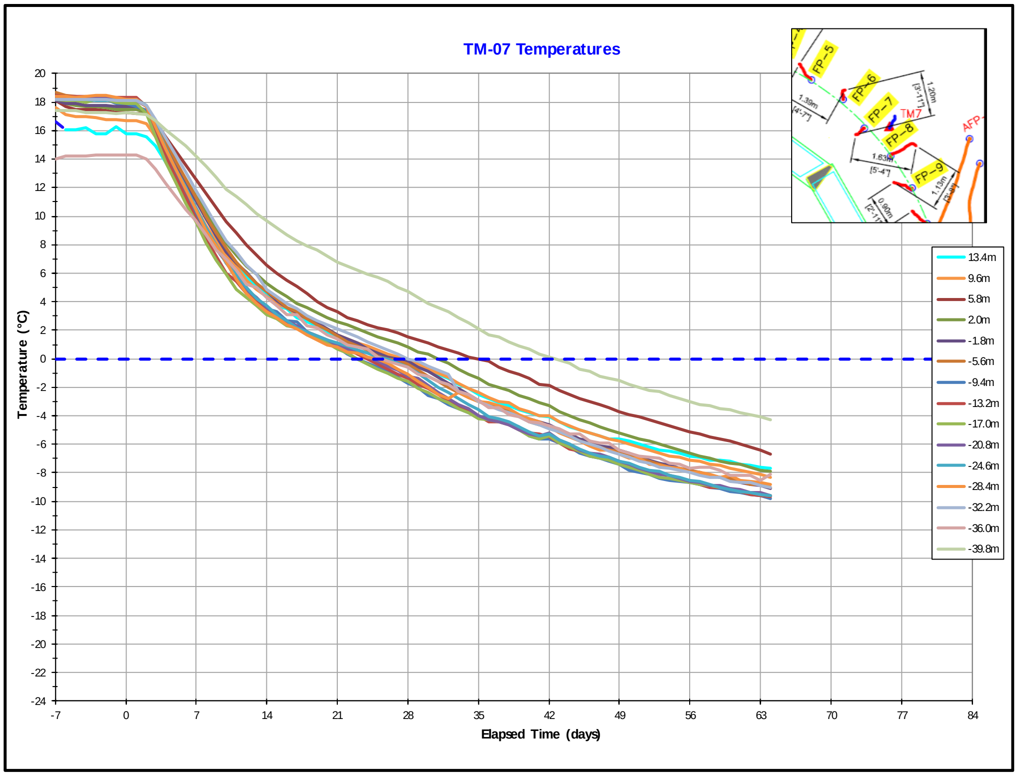

Figure 6. Temperature vs. Time in TM-07

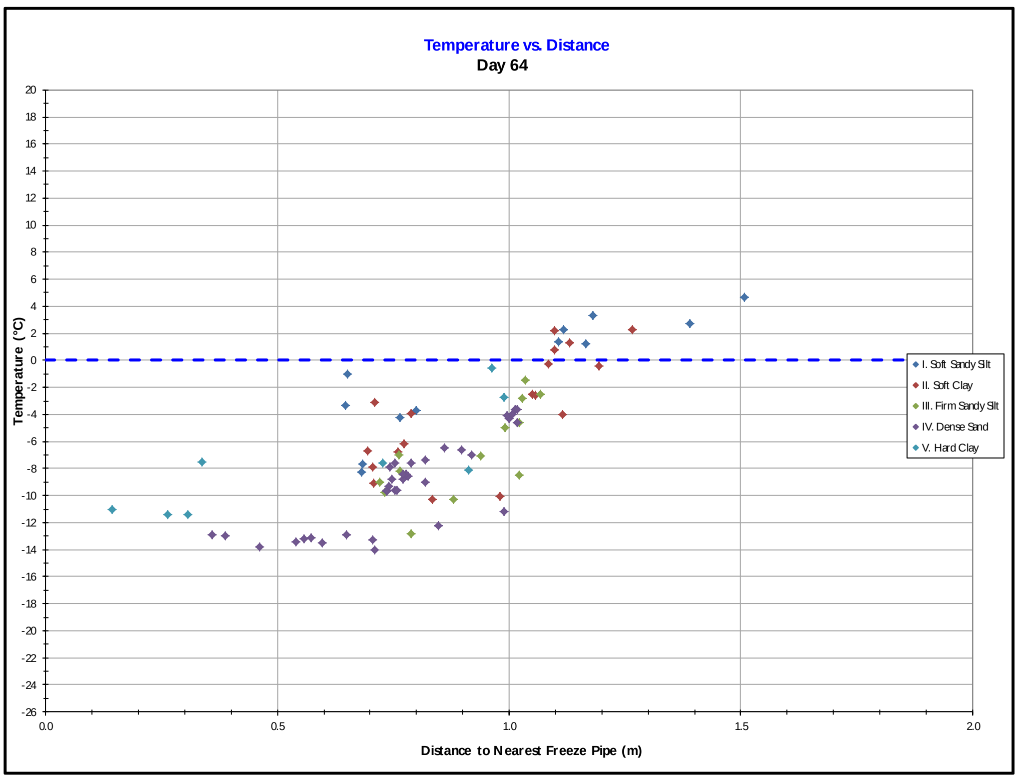

Figure 7. Temperature vs. Distance to nearest freeze pipe

2. **Freezing time:** Figure 6 demonstrates a typical trend of temperature versus time. The soil cooled rapidly at the outset, then slowed as it approached the phase change from liquid water to ice.
3. **Distance from the freeze pipes:** Sensors closer to freeze pipes cooled more quickly. By plotting temperature versus the distance between from sensor to the nearest freeze pipe, as in Figure 7, the thickness of the frozen wall can be approximated. On Day 64, all sensors within 1.1 m of a freeze pipe were below 0 °C, implying that the frozen wall was roughly 2.2 m thick by that date.

The data suggested that the frozen soil had fully formed into a watertight wall by Day 64. Closure of a frozen shaft is normally indicated by a rise in water elevation inside the shaft; since CA3 had an existing concrete structure that affected groundwater response, it was more difficult to determine closure. For confirmation, the shaft was evacuated in a controlled pump-down test over a period of 4 days. The water level of the shaft was continuously monitored and compared against the piezometer levels. This ensured that there was no communication between the water level inside the shaft and the phreatic surface outside.

Shaft Excavation

Concurrent with the formation of the frozen soil wall, the joint venture installed the concrete reinforcing rings and the masonry plugs recommended by the structural engineer. Once the ground freezing subcontractor confirmed closure, the JV proceeded with installation of the final shaft liner. They excavated the soil around the tunnel, removed the tunnel segments, and poured a concrete slab at the base of the shaft. Plugs of grout and soil were visible in some exposed slurry panel joints as shown in Figure 8. During the Argentine summer ambient temperatures reached as high as 36 °C, but the ground

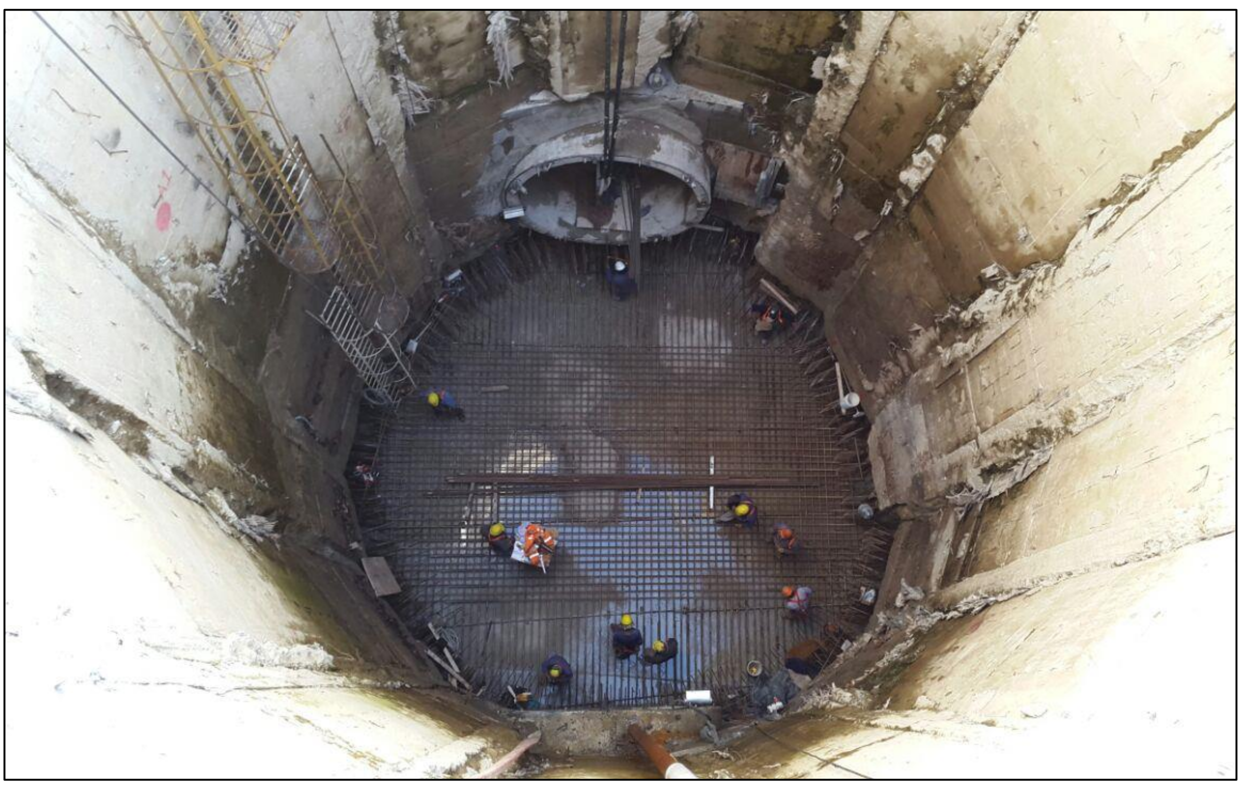

Figure 8. After removing the tunnel segments, the joint venture prepared the base of the final liner

freezing system kept the air temperature at the base of the shaft a cool 11.5 °C.

The ground freezing system remained in operation until the JV installed the final shaft liner above the level of the known leaks in the slurry wall. The system was turned off after 147 days of operation. No noticeable heave or settlement was observed at ground surface.

CONCLUSION

When other ground improvement methods were unsuccessful in stopping the leaks at Access Shaft 3, ground freezing provided a unique solution. The difficult conditions on this project were overcome through collaboration and careful planning during the design, installation, and operation phases:

- The soil pressures did not cause any damage to either the tunnel or the shaft structures, validating the structural model;
- The estimated freezing time was in close agreement with actual field conditions, confirming the accuracy of the thermal model;
- After more than two years of difficulties, ground freezing enabled the joint venture to successfully excavate and construct Access Shaft 3.

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- **Structural consultant:** Halcrow
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