Tunneling Through Soft Ground Using Ground Freezing

Ground freezing represents a viable solution to create a watertight and load-carrying soil body in water-bearing soil.

HELMUT HASS

The ground freezing method was developed in the nineteenth century by the German engineer Friedrich Poetsch. The method was developed to sink shafts through water-bearing soils down to hard rock and coal seams. It was the only safe method to construct shafts with depths of more than 50 meters (160 feet) in water-saturated soil. The deepest freezing shaft completed so far in Germany was in Rheinberg with a depth of more than 600 meters (1,925 feet). Figure 1 shows the original patent document for this method, which was dated 1883.

Ground freezing is a process where in-situ pore water is converted to ice. Like the cement in concrete, the ice bonds the soil particles together, imparting strength and impermeability to the frozen soil mass. Ground freezing is based on withdrawing heat from the soil. A continuous supply of energy is usually required to establish and maintain a frozen soil body.

In order to freeze a body of soil, a row of vertical, horizontal or inclined freeze pipes have to be drilled into place. An open-ended inner pipe (sometimes referred to as the down-pipe) is inserted into the center of the closed-end freeze pipe (see Figure 2). The down pipe is used to supply the freeze pipe with a cooling medium, usually brine or liquid nitrogen. The inner pipe is connected to the supply line and the outer pipe to a return line (when brine is used) or an exhaust line (when liquid nitrogen is used). The coolant flows through the inner pipe to its deepest point. On its way back through the annulus between the inner (down) pipe and freeze pipe, the coolant picks up heat from the soil and warms. Due to the flow of the coolant, the frost penetrates outward from the pipe into the soil and a ring of frozen soil occurs around the freeze pipes as heat is withdrawn. Freezing generally occurs initially at the bottom depths and progresses upward. Depending on the arrangement of the freeze pipes, all shapes of frozen soil walls (bodies) can be achieved as required for an individual task.

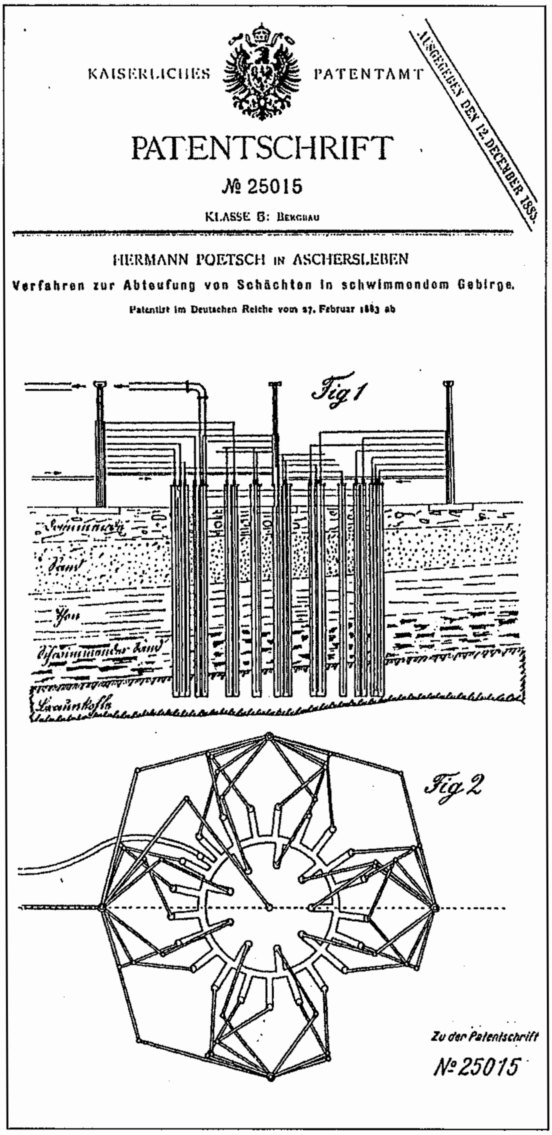

FIGURE 1. A ground freezing patent document from 1883.

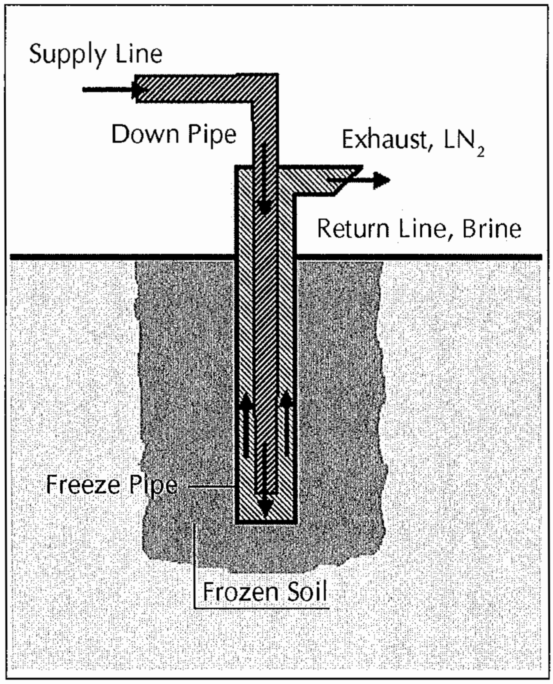

FIGURE 2. A diagram showing the ground freezing principle.

Brine freezing requires a closed circulation system and the use of refrigeration plants. The brine (usually water mixed with calcium chloride, $CaCl_2$) picks up heat at the bottom of the down pipe, then it flows back through the insulated surface manifold system before returning to the freeze plant for recooling in the vaporizer. The principle of brine freezing circulation is presented in Figure 3. The brine supply temperature, T, generally ranges from –20 to –37 degrees Centigrade (–4 to –35 degrees Fahrenheit).

The entire freezing plant consists of the required number of freeze units, several additional components (such as low voltage switch-gears), tanks for the brine backflow and the back cooling units (cooler) that remove heat from the warmed cooling agent. Several freeze units can be combined in a more powerful freeze plant. To minimize fresh water consumption, special recooling systems should be connected for heat exchange with the air. Currently, it is state of the art to use ammonia as the cooling agent to remove the heat. Ammonia is much more environmentally friendly than hydrocarbon fluoride (Freon), which was used until 20 years ago.

With liquid nitrogen freezing, heat is extracted from the soil through direct vaporization of a cryogenic fluid (LN_2) in the freeze pipes. From an on-site storage tank or directly from a tank truck, the LN_2 is fed through an insulated surface manifold system, usually consisting of copper pipes and quick-connect cryogenic hoses, into the inner pipes as shown in Figure 4.

The LN_2 starts to vaporize at a temperature of –196 degrees Centigrade (–321 degrees

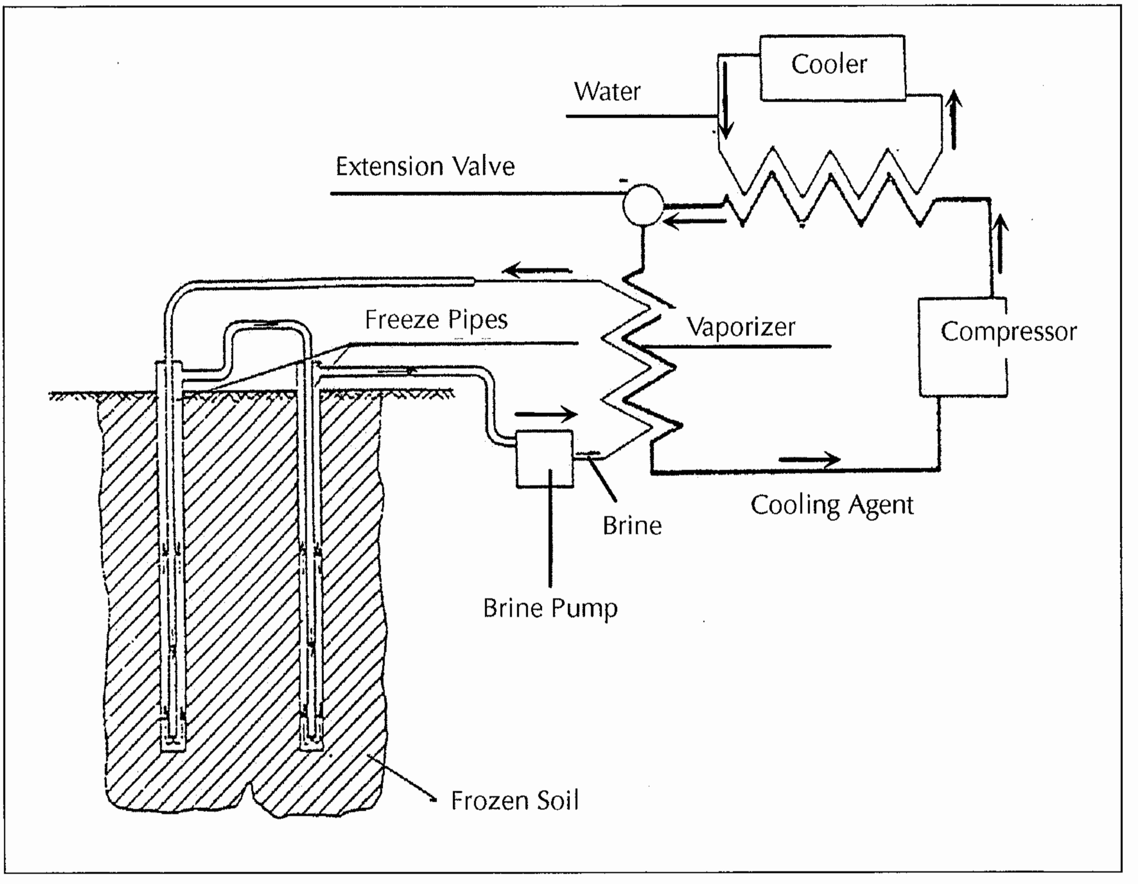

FIGURE 3. Typical set-up for brine freezing.

Fahrenheit) in the annulus between the freeze and inner pipes, picking up heat on its way up. The cold nitrogen gas is directly vented into the atmosphere; the gas exhaust temperature is measured with temperature sensors. The amount of LN_2 that is fed into the inner pipe is controlled by a cryogenic two-way solenoid valve. The solenoid valve is controlled by the nitrogen gas exhaust temperature, and either opens or closes based on preset temperature limits.

Freezing with LN_2 is fast. A frozen soil body can be formed within a matter of a few days with LN_2; whereas it takes weeks for the brine freezing system. However, due to its high cost, the use of LN_2 for ground freezing is usually limited to short-term applications or limited volumes of frozen soil.

The Behavior of Frozen Soil

The behavior of frozen soil under quasi-static loading usually differs significantly from that of unfrozen soil due to the presence of ice and unfrozen water films. Freezing will increase the strength and stiffness of the soil. However, frozen soils are much more subject to creep and relaxation effects and their behavior is strongly affected by temperature changes. The viscoelastic behavior of ice is dependent on many additional factors, such as salinity, pressure, strain rate, crystal orientation and density.

Time-Dependent Creep Behavior. Figure 5 shows typical idealized curves of creep and corresponding strain rate versus time, assuming constant stress and isothermal conditions. Three distinct phases, or stages, of creep are usually evident. After an instantaneous strain (elastic deformation), the primary phase, or Stage 1, is characterized by strengthening with a continuously decreasing strain rate. The secondary or steady-state creep phase, or Stage 2,

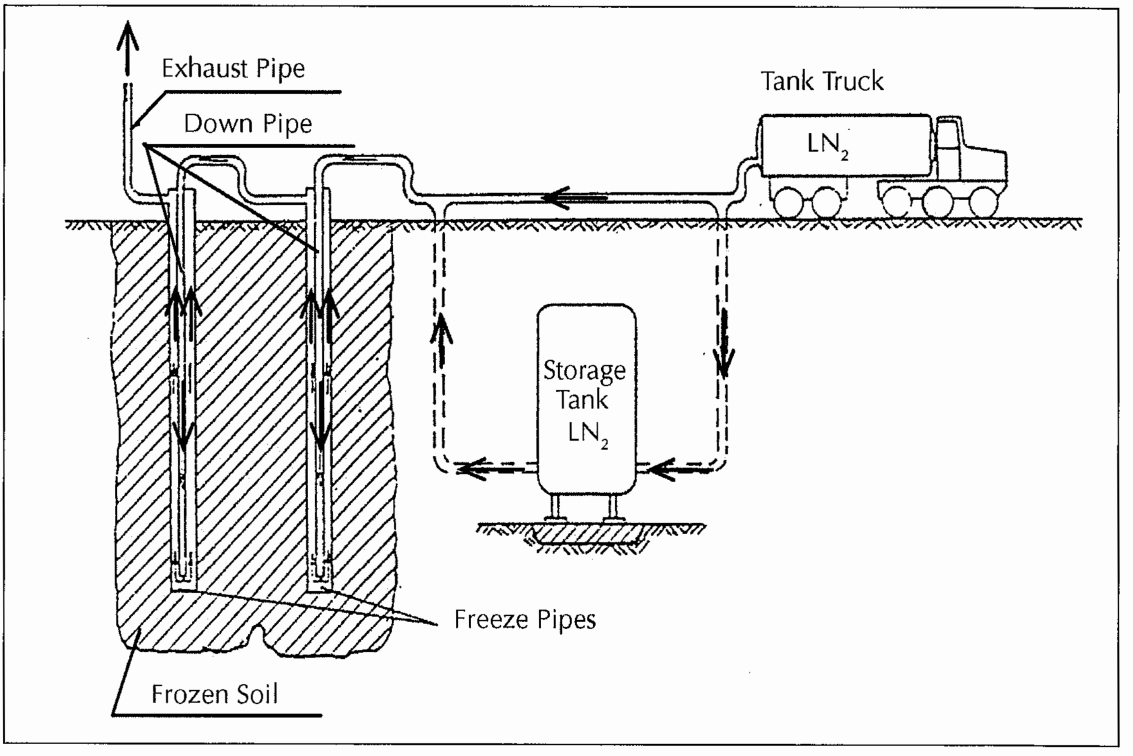

FIGURE 4. Typical set-up for liquid nitrogen freezing.

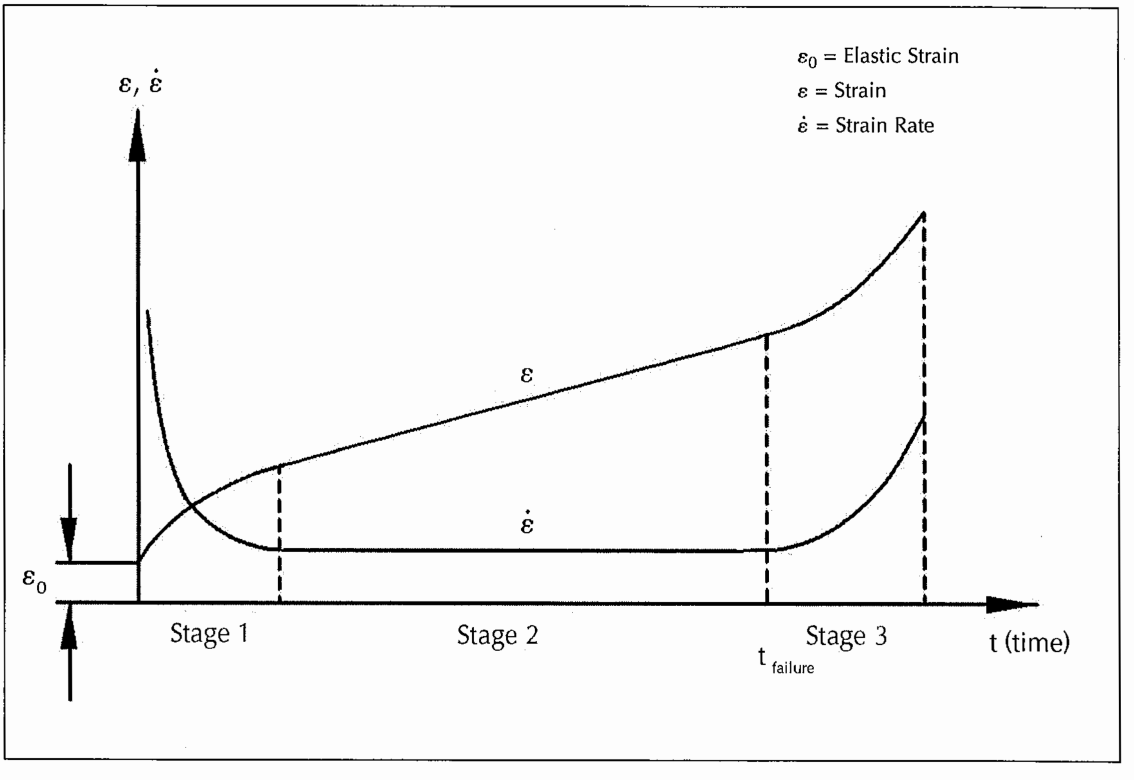

FIGURE 5. A typical creep curve for frozen soil.

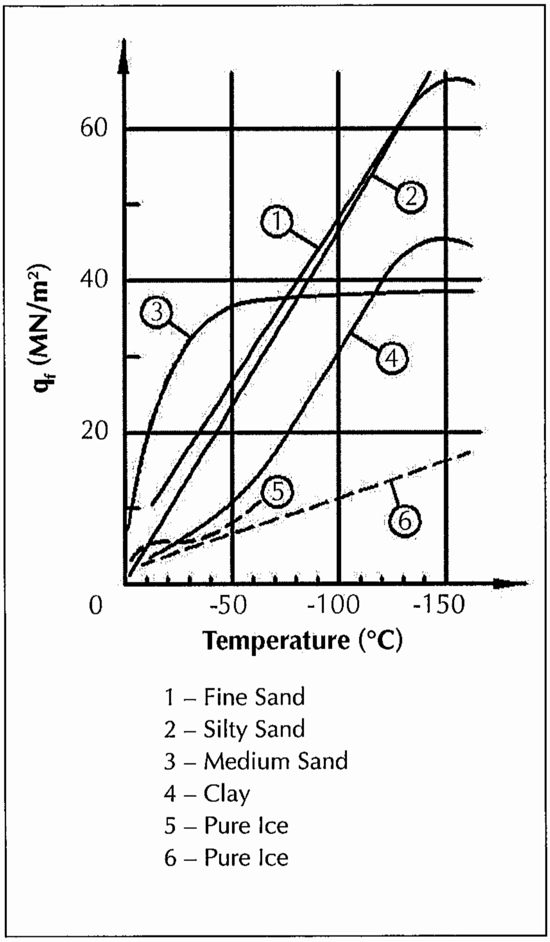

FIGURE 6. Frozen soil strength versus temperature.

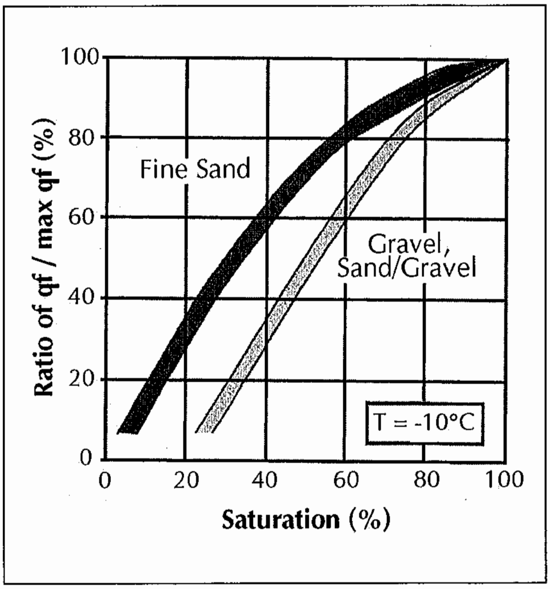

FIGURE 7. Frozen soil strength versus saturation.

is characterized by a constant creep rate, which is the minimum rate reached during the test. Finally, the tertiary phase, or Stage 3, is characterized by an accelerated creep rate, which leads to the ultimate failure of the specimen. Because of the creep behavior of frozen soil, a decrease of strength and stiffness from 40 to 60 percent of the initial values has to be considered, depending on the time period of ice service on a project.

Temperature-Related Behavior. The uniaxial unconfined compressive strength, q_f, of the frozen soil is an important value for the structural design, as is the Young's modulus of elasticity, E. These parameters are not only time dependent, they are also strongly dependent on the temperature. In Figure 6, the uniaxial strength versus temperature is shown for specific soil layer tests conducted in the lab on a range of typical soil types and for pure ice. (The curves shown in Figure 6 are based on lab test results from a project in Düsseldorf, Germany.)

The average temperature of frozen soil usually ranges from –5 to –25 degrees Centigrade (23 to –13 degrees Fahrenheit) and the lowest temperature is usually not colder than –50 degrees Centigrade (–58 degrees Fahrenheit). In this range, the strength behavior of frozen soil is almost linear.

Influence of Water Saturation. The strength and the stiffness of the frozen soil also depend on the degree of water saturation as the frozen water bonds the soil particles. Figure 7 shows the compressive strength of frozen soil versus the degree of water saturation. With a saturation of 40 percent, fine sand has a compressive strength of approximately 60 percent of its maximum strength (a saturation of 100 percent). Given the same saturation, gravel achieves approximately 35 percent of its maximum value.

Frost Heave. Another property that has to be considered is the frost heaving of frost-susceptible soil. Figure 8 shows typical curves of frost heave rate versus permeability. Frost heave is reduced as overburden pressures

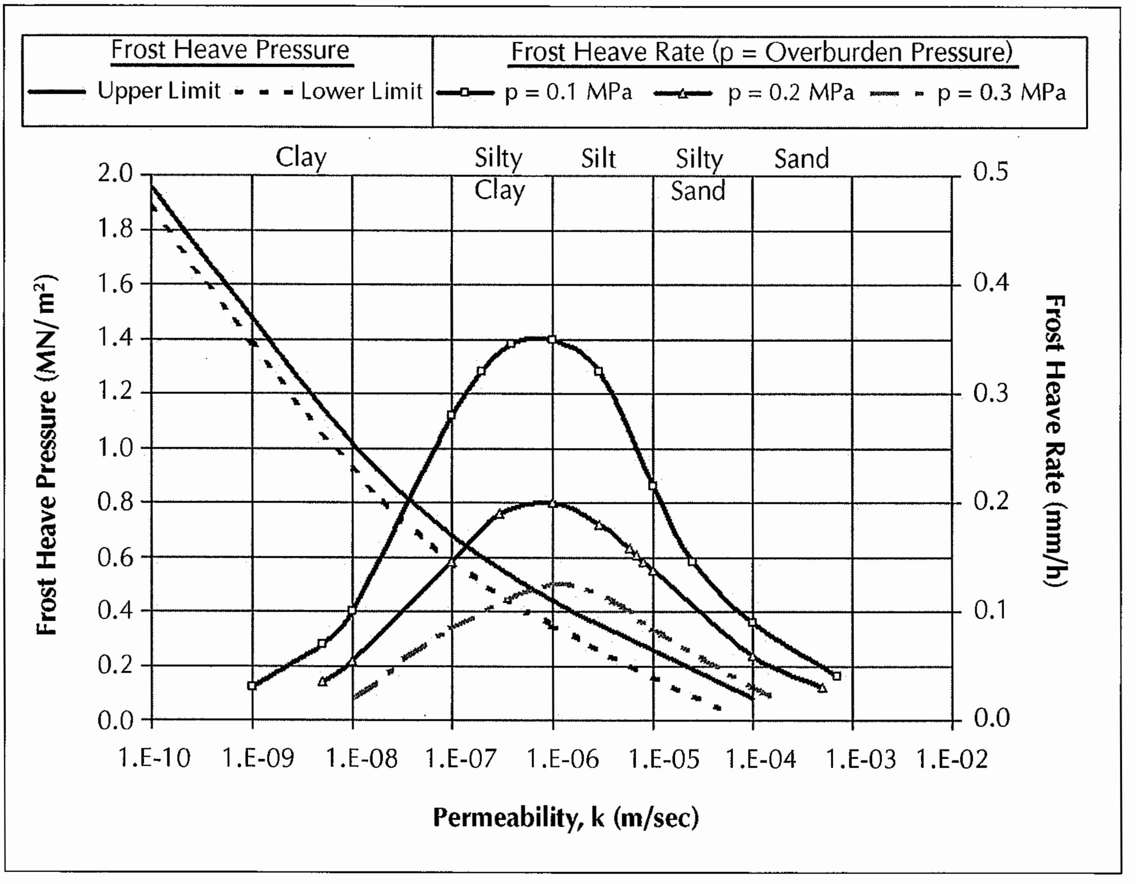

FIGURE 8. Frozen soil frost heave behavior.

increase. Therefore, three curves for different pressures are shown. The diagram also shows curves of possible frost pressure that may occur if the soil is confined due to local conditions. It is notable that the highest frost heave occurs in soil with a permeability of 1×10^{-6} to 1×10^{-7} meters (0.00004 to 0.000004 inches) per second. This permeability is typical for silt or silty clay. The highest frost pressure can occur in clayey soils.

Groundwater Velocity. Groundwater flow can have a major impact on the freezing operation. Flowing water provides a continuous source of heat, and can significantly delay the freezing time. In a worst-case scenario, a state of thermal equilibrium can be reached in which the soils stop freezing and closure (merging of the frozen soil cylinders of adjacent freeze pipes) of the freeze wall cannot be achieved.

As a rule of thumb, effective flow velocities (seepage velocity) of less than 2 meters (6.5 feet) per day for brine freezing and 4 to 6 meters (13 to 19 feet) per day for LN_2 freezing seem to have little or no effect on the freeze wall development. For higher groundwater flow rates, the following measures can help ensure timely formation of the freeze wall:

- reduced freeze pipe spacing;
- installation of additional freeze pipes (second or third row) preferably on the upstream side;
- lowering of the brine temperature through increased refrigeration capacity;
- use of liquid nitrogen in critical areas;
- grouting to reduce permeability and groundwater flows to acceptable levels; and,
- installation of intercepting wells to reduce the groundwater gradient.

Application of Ground Freezing

Ground freezing is mostly used for temporary ground support or as temporary structural elements or as a groundwater control system. The advantage of frozen ground is that frozen water is 100 percent impermeable soil. Obstacles like stones, concrete remnants or similar materials, which cause problems when grouting techniques are used for sealing tasks, will just be embedded in the frozen soil volume as the frost grows through and around the obstacles.

Ground freezing is being used in underground construction projects for:

- sinking and lining of deep mineshafts to depths of more than 600 meters (1,925 feet);
- deep excavations (shafts);
- tunneling using the sequential excavation method (SEM) under the protection of a structural and watertight frozen soil body;
- cross-passages between shafts and tunnel tubes, or between tunnel tubes;
- large open excavations, retaining walls;
- temporary soil improvement under foundations;
- temporary sealing of leaks; and,
- temporary water cut-off for connections at the interface between existing and new underground structures.

Ground freezing is environmentally friendly since no barriers (such as diaphragm walls, chemical grouts or other grouting materials) remain in the ground after the application. Ground freezing can also be used for environmental applications such as freezing the soil of a landfill to keep the contaminated material in the soil from spreading during excavation.

Investigation & Lab Testing

Groundwater Conditions. Groundwater flow can have a major impact on the freezing operation. The hydraulic conductivity, *k*, and the groundwater gradient on the site must be ascertained to evaluate any existing groundwater flow conditions. Attention must be paid to possibly increased flow velocities in localized zones of coarse-grained layers. Existing or planned nearby dewatering measures may also influence the groundwater flow and may cause high groundwater velocities.

Observation wells upstream and downstream of the frozen soil body have to be installed. Investigation of the existing groundwater flow conditions can be conducted by using single borehole testing in observation wells. These tests should encompass:

- Dilution tests using dyes and other tracers. With this test, the groundwater flow direction and velocity can be determined for each layer versus depth.
- Determination of the permeability over the whole depth with flowmeter tests.

In case tracer tests cannot be performed, the permeability of each layer should be determined by using flowmeter tests and should be based on grain size distribution. Based on the groundwater level gradient, the flow direction and velocity can be estimated.

Subsurface Conditions. It is strongly recommended to investigate the existing soil conditions by using drilling methods with continuous undisturbed sampling to get a continued soil profile over depth that reveals all existing layers. The core diameter should be at least 50 millimeters (2 inches), but sizes of 75 to 100 millimeters (3 to 4 inches) are preferred.

Laboratory Testing Program. A test program for ground freezing purposes is required to verify the estimated soil parameter values or to determine the actual range of soil parameters in frozen and thawed conditions. The test program has to be conducted by experienced personnel in a laboratory specially equipped to evaluate frozen samples.

The test program should provide at least the following information about the soil layers at the construction site:

- Index properties: grain size distribution, specific gravity dry unit weight, Atterberg limits, degree of saturation, salinity;
- Frost deformation behavior in case the soil is frost-susceptible (frost heave tests); and,
- Geotechnical soil properties on unfrozen, frozen and thawed samples. These tests should be performed on soils taken from the boreholes at the site to determine: temperature-dependent shear strength,

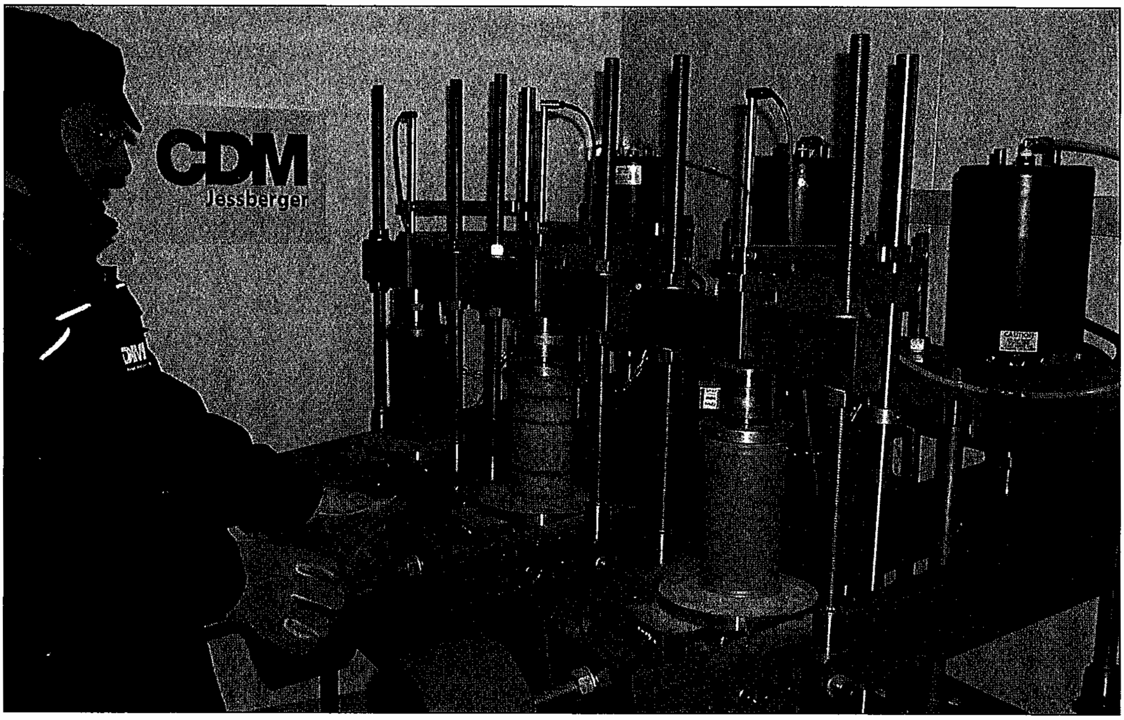

FIGURE 9. Frozen creep tests in a special laboratory.

temperature-dependent unconfined compression strength, and time- and temperature-dependent creep behavior (see Figure 9).

Based on the results of the lab test program, the temperature- and time-dependent frozen soil design parameters can be specified as input data for the final design.

Design of Ground Freezing Applications

Thermal and structural calculations are required for the design of a ground freezing project. The thermal design determines the freezing time to form the freeze wall, freeze plant capacity, freeze plant operation during maintenance freezing and temperature development, as well as temperature distribution in the soils. The structural design provides the dimensions of the freeze wall and the required average freeze wall temperature.

Thermal Design. The thermal design can be based on rough calculations for the freeze wall growth and the heat flux using analytical methods during a pre-design phase. In most final designs, thermal calculations using the finite-element method (FEM) are required to verify results of the pre-design and to optimize the freeze pipe spacing and arrangement as well as freeze plant capacity. Using this method, the actual conditions (freeze pipe spacing and location, interrelation of adjacent freeze pipes, dependencies of freeze wall growth between different layers, etc.) can be effectively varied and optimized. For the actual thermocouple locations, these calculations can predict time-dependent temperatures that can then be used for direct comparison with the actual thermocouple readings during the freezing operation.

Using the numerical finite-element method, the following design conditions can be considered:

- different soil layers;
- different initial temperatures in the soil layers;
- varying freeze pipe spacing and varying freeze pipe temperatures;
- different and temporarily changing freeze plant capacities for brine freezing;

- intermittent freezing during maintenance; and,
- additional heat sources or thermal boundary conditions.

The results of the analyses should include:

- the time-dependent development of the frozen soil body;
- the average frozen soil temperature to verify the time-dependent frozen soil parameter (e.g., strength, stiffness, etc.) used for the structural design;
- the time required to freeze the designed frozen soil body;
- optimization of the freeze pipe arrangement and freezing operation;
- the time-dependent temperature distribution in the soil;
- determination of energy consumption; and,
- design of the capacity of the refrigeration plant (for brine freezing).

Figure 10 shows the temperature distribution in a frozen soil body after a certain freezing time from a thermal FEM analysis.

Structural Design. Structural design is required when the frozen soil body serves both as structural element and to cut off water. For many practical applications, it is sufficient to check the stress in the structural design of the freeze walls. The required structural design data for the allowable stress — Young's modulus and shear parameters — will be determined using the projected frozen soil stand-up time.

The basis for the sound structural design of a load-bearing frozen soil structure is extensive knowledge of the time- and temperature-dependent strength and deformation properties of the material. Frequently, the complex time-dependent stress-strain characteristics are simplified for the structural design. However, in some cases, the entire stress-strain-history from the start of loading has to be considered. Detailed time-dependent solutions can be reached by using numerical methods. Strength properties of the frozen soil body change according to the temperature distribution throughout its cross section. Whereas the strength is highest in the center of the frozen soil body, strength decreases towards its boundaries (0 degree Centigrade [32 degrees Fahrenheit] isotherm for fresh water). Due to this fact, it is possible that the stress at the boundaries exceeds the load support capacity of the soil body. In this case, plastification and subsequent stress redistribution will take place. The resulting stress distribution is now similar to that of the temperature distribution.

Final structural analysis of the freeze wall can be performed using FEM. Frozen and unfrozen soil stress-strain behavior can be simulated with a non-linear model. The advantage of using FEM is that it realistically accounts for both the frozen and the unfrozen soil. A major disadvantage of a more direct analytical approach is that it uncouples the frozen soil wall from the surrounding unfrozen soil and the external loads of earth and water pressure (plus any surcharge loads that are applied to the freeze wall).

The calculated deformations should include the effects of:

- excavation (stress relief and redistribution); and,
- creep characteristics of the frozen soil thawing.

Depending on the wall shape (straight or curved), the frozen soil body may only take limited loads; therefore, the design of additional support measures is required. These additional measures may consist of shotcrete application, or support measures such as anchors, beams or similar structures.

Design of Freeze Plant Capacity. The required capacity of the freeze plant (brine freezing) or the required amount of liquid nitrogen depends, among other things, on the number and length of freeze pipes, the total volume of the frozen soil, the freeze time and the required freezing temperature. In addition, the freeze plant must also be integrated into the construction program. A freeze plant may consist of several freeze units that are connected to one system based on the required capacity. After the freeze wall is built up to its required shape and thickness, it is usual practice to provide an intermittent level of cooling that is needed for the maintenance of the

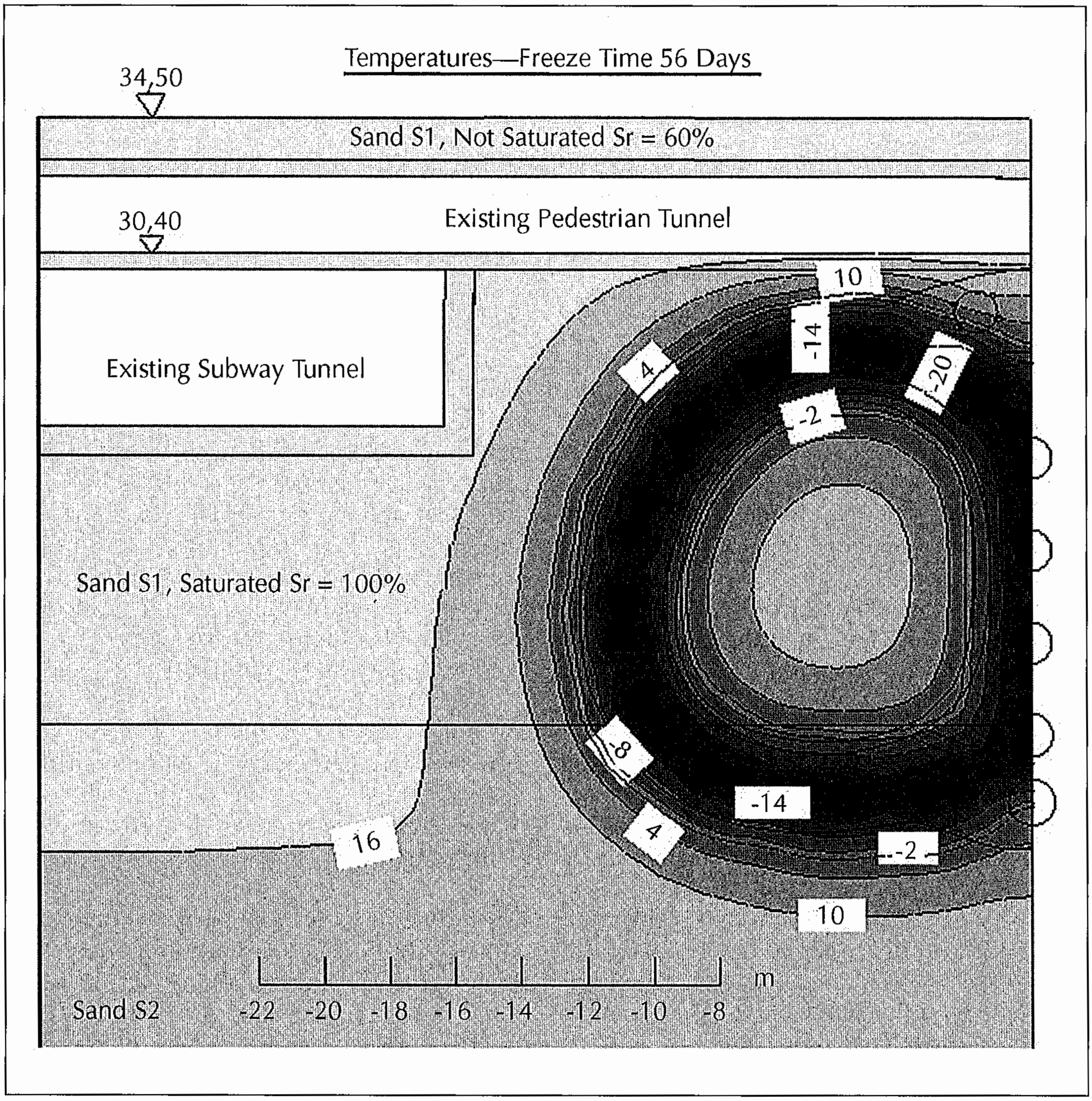

FIGURE 10. Results of a thermal FEM analysis.

frozen wall. Its capacity and its time-dependent development will be based on the thermal design analysis (as discussed above).

Risk Analysis. A sufficient risk analysis and appropriate measures to deal with these risks should be provided. Potential risks are:

- deviation of freeze pipe drillings;
- areas with unexpected high groundwater velocity;
- high groundwater salinity or contamination;
- inexperienced contractor;
- unexpected leakages;
- frost heave deformations;
- freeze plant/unit failure; and,
- electricity power failure.

Monitoring & Quality Control During Conduction

The construction of the frozen wall has to be monitored. Aside from measuring the temperature of the cooling agent, soil temperature measurements are of utmost importance. All essential data should be collected in one place and analyzed with computer-supported methods.

The following measurements should be taken to check the operation of the freeze system:

- temperature at the inlet and outlet of the freeze plant (brine) or the tank (LN_2 outlet), as well as flow and return temperatures of the brine;
- pressure of the cooling agent at the pressure side of the pumps and at the collecting main (brine freezing);
- the flow volume of the brine in particular locations;
- the liquid level in the brine collecting tank;
- the density of the cooling agent; and,
- the brine (or nitrogen exhaust) temperature should be monitored at every single return (exhaust) line, checking the proper cooling agent flow.

To check and control the freezing process, temperature measurements in the soil are strongly required. The spacing of thermocouples in temperature holes should be adjusted to the expected critical areas. In the area of the expected conditions (critical layers, freeze wall connection to structures, etc.), the thermocouple or monitoring hole spacing should be reduced. Figure 11 presents the time-dependent development of the frozen soil thickness based on temperature monitoring data that is compared with results based on thermal FE-calculations.

It is important to survey the actual location and deviation of each and every freeze pipe and temperature monitoring pipe. The temperature readings for monitoring can only be evaluated sufficiently if the exact location of each thermocouple and their distances from the two closest freeze pipes are known, because high temperature gradients may occur in some areas of the frozen soil. Otherwise, it is not possible to properly evaluate the temperature data and to obtain the right assessments.

Based on the survey data of all the pipes, the actual location of the pipes can be evaluated to determine if the freeze pipe spacing is sufficient at all locations. If required, additional drillings can be conducted before the freezing operation starts. The actual location of the freeze pipes and the thermocouples can be incorporated in the thermal FE model and the predicted time-dependent temperatures can be used for direct comparison with the related thermocouple readings during the freezing operation.

To guarantee the tightness of the freeze pipes, pressurization tests inside every pipe are strongly recommended before the freeze supply lines are connected. If freeze pipe leakages occur, brine would penetrate into the soil and would cause the immediate thawing of the frozen soil in that area. Depending on the amount of brine that has leaked, serious problems with the freeze wall can occur.

The monitoring program should also measure for deformation. These measurements should include:

- frost heave measurements of existing buildings or structures and the ground surface;
- inclinometer, or similar measurements, in the structural frozen soil body; and,
- extensometer measurements to check frost heave deformations in the subsurface.

There should also be pore pressure monitoring using pressure transducers, as well as groundwater level monitoring.

Completed Projects

Subway Section 3.4H, Düsseldorf, Germany. As part of the Düsseldorf mass transit subway system expansion, four 40-meter (128-foot) long tunnels were excavated directly below buildings and a major roadway. All four tunnels were advanced using SEM (formerly called the New Austrian Tunneling Method [NATM]). In each case, there was very little space between the roof of the tunnel and the bottom of the overlying building foundations. As a result, any ground loss, or other causes of settlement due to tunneling, would have led to direct and adverse movement of the existing building foundations.

The individual tunnels were located in granular soils. The general soil profile consisted of intermittent changing Quaternary sand

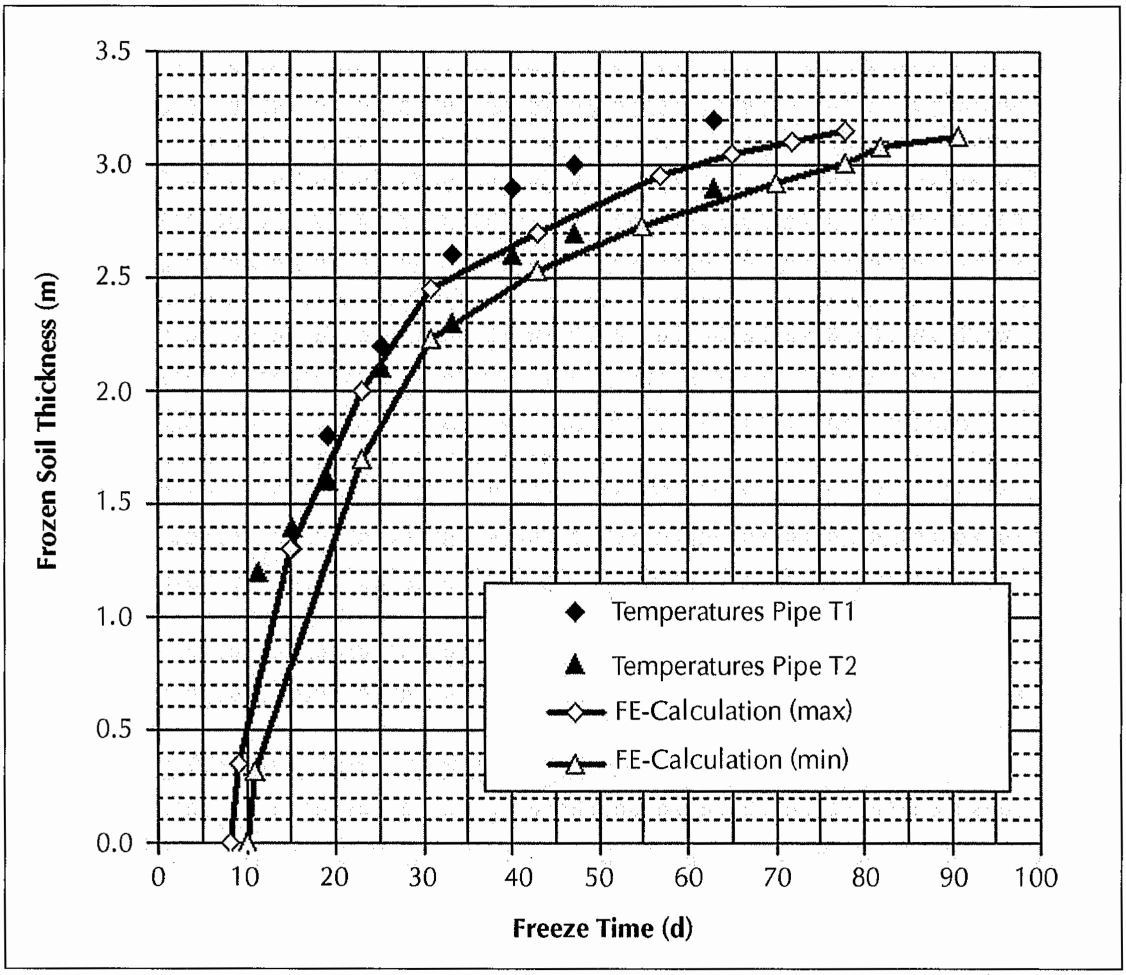

FIGURE 11. A comparison of temperature monitoring and FE-calculation results from the Westerscheldetunnel in the Netherlands.

and gravel layers. Underlying this stratum was very dense Tertiary fine sand.

For the driving of three of the tunnels, the gravel and sands were stabilized and the groundwater was controlled by ground freezing using a brine coolant (see Figure 12). Table 1 lists the data of the three frozen soil bodies for Tracks 1, 3 and 4.

For the ground freezing operation of the three tunnels, a freeze plant of two units with an operating brine temperature of –35 degrees Centigrade (–31 degrees Fahrenheit) and a capacity of 330 kW each were used. The freeze plant was installed in an isolated hall because of the urban residential area.

A unique feature of the ground stabilization for this project involved the freezing of natural unsaturated soil above the groundwater table. To ensure that the soil mass to be frozen had an adequate bearing capacity, water was injected into the soil. To do this, vertical cut-off walls were grouted along the sides of the tunnel to reduce the run-off of water injected into the soil. Water injection and freezing were conducted in four phases (see Figure 13).

All of the tunnels were driven without incident and with only negligible subsidence to the buildings and the main road directly above the tunnels. Figure 14 shows the very close distance from the buildings to the tunnel of Track 1 and the highly demanding urban conditions. The access shaft was located in the backyard of two residential buildings.

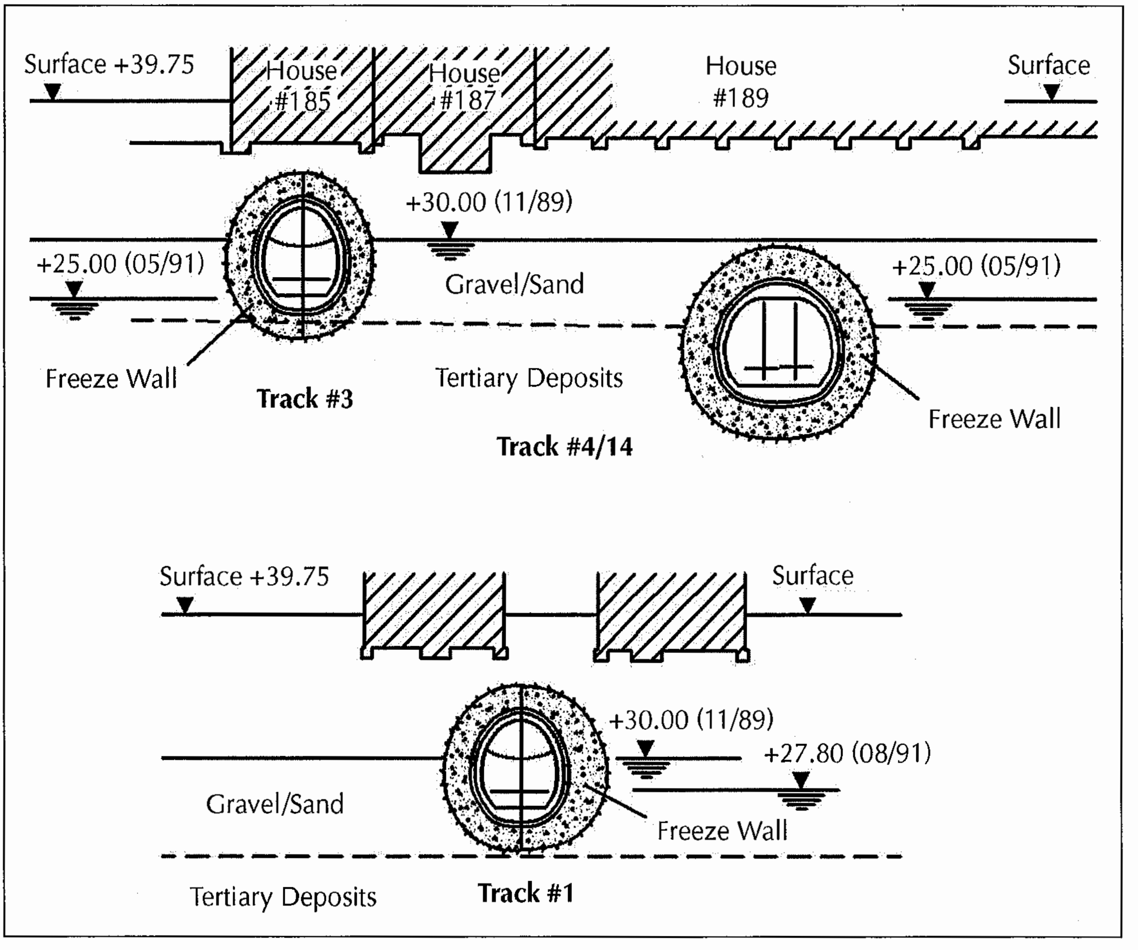

FIGURE 12. Cross-sections of the three track tunnels on the Düsseldorf subway project where brine ground freezing methods were applied.

Fahrlachtunnel in Mannheim, Germany. To relieve urban traffic congestion, the city of Mannheim in Germany built the Southern Expressway. The alignment required the construction of a 305-meter (978-foot) long tunnel that passes beneath a wide rail corridor with eleven frequently used railroad tracks in downtown Mannheim. During the entire con-

TABLE 1.
Data for the Düsseldorf Subway Project

	Top of Frozen Soul Below Foundation, m (ft)	Excavation Zone, m^2 (ft^2)	Frozen Soil Length, m (ft)	Frozen Soil Volume, m^3 (ft^3)	Frozen Soil Thickness, m (ft)
Track 1	0.6 (2)	46 (495)	48 (154)	1,600 (56,503)	1.5 (5)
Track 3	1.8 (6)	42 (452)	40 (128)	2,600 (91,818)	1.5 (5)
Track 4	6.7 (21.5)	75 (807)	40 (128)	2,900 (102,412)	2.2 (7)

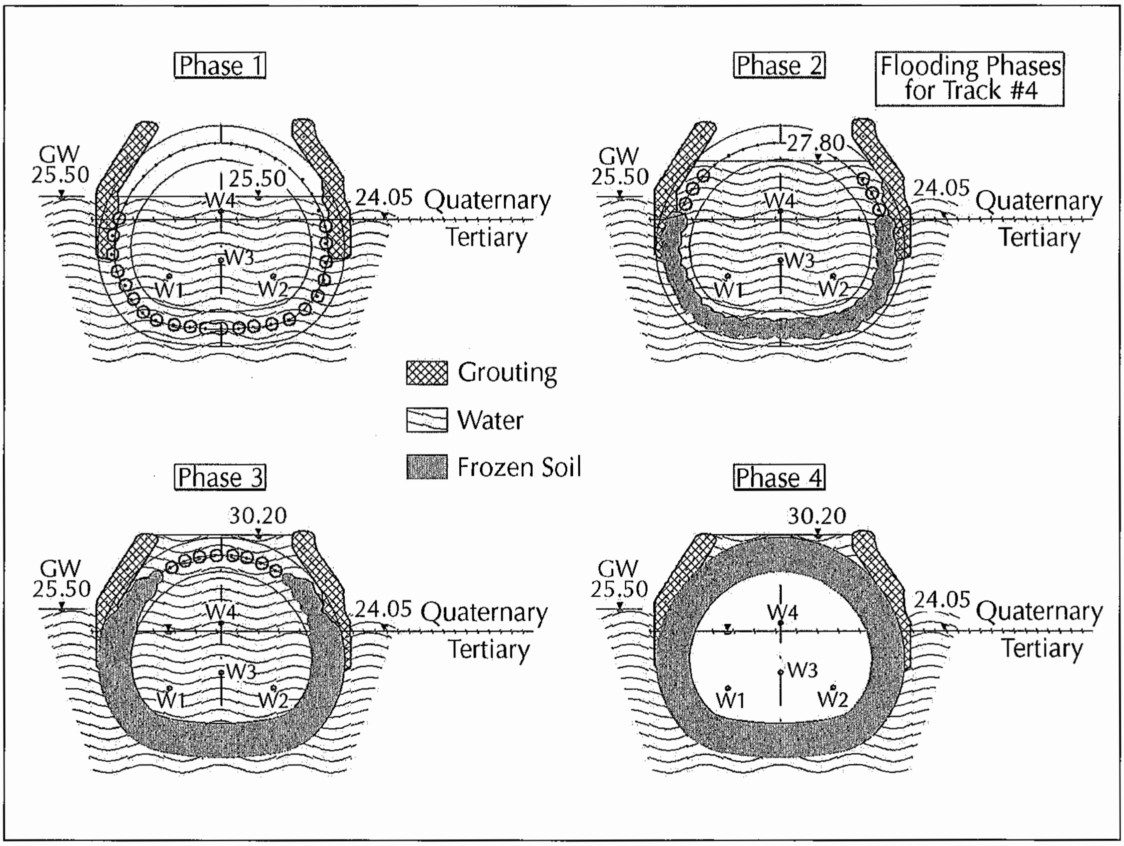

FIGURE 13. Water injection and freezing phases for the Düsseldorf subway project.

struction time no interruptions to the high-speed railroad service were to be tolerated.

The tunnel was divided in two cut-and-cover sections and one 184-meter (590-foot) long section directly underneath the railroad tracks. That section was advanced using SEM under the temporary protection of a structural and watertight frozen soil ring. The construction method was based on an alternative approach (value engineering) submitted by the contractor (joint venture). Figure 15 shows a model of the tunnel alignment and the railroad tracks.

The temporary frozen tunnel was located in very heterogeneous soil. The general soil profile consisted of a 4-meter (13-foot) fill layer followed by a 2-meter (6.5-foot) silt layer. Below the clay were alternating layers of sand and gravel with thicknesses ranging from a few centimeters to several meters. There was also a wide range of grain size distributions. The groundwater level ranged from 3.5 to 7.5 meters (11 to 24 feet) below the surface. A schematic longitudinal section with the geological profile is shown in Figure 16.

The top of the frozen tunnel was very close to the railroad tracks and the frozen soil body was partly above the groundwater level. The water saturation in this area had to be artificially increased to achieve the required strength of the frozen soil. An additive was administered to the water in order to increase its viscosity, thereby slowing the flow of the artificial watering. In addition, grouting measures were conducted to reduce the groundwater velocity in layers with high permeability.

The frozen tunnel length was divided by a transverse frozen soil bulkhead across its length. The width was also divided so that, in total, four tunnel-drifts, each 90 meters (289 feet) long, were advanced by using SEM. Figure 17 shows a cross-section of the tunnel using ground freezing.

An auxiliary tunnel with a diameter of approximately 2.4 meters (8 feet) was

FIGURE 14. Access shaft of the tunnel of Track 1 on the Düsseldorf subway project.

advanced above the groundwater level using SEM in order to install the freeze pipes for the transverse bulkhead as well as the pipes for water injection and grouting.

The drilling for the installation of the longitudinal freeze pipes started with conventional small-diameter drilling techniques from both sides towards the frozen soil bulkhead. The deviations of these shafts were so great that the required accuracy could not be achieved over the entire drilling length of 90 meters (289 feet). The accuracy was only acceptable for lengths between 40 to 50 meters (128 to 160 feet), which was not sufficient for the project. To solve this problem, microtunneling was required. The microtunneling technique used to install the long freeze pipes utilized a diameter of 47 centimeters (18.5 inches) to obtain the required accuracy. Overall, 86 microtunnels were drilled. Each tube contained two freeze pipes. After the installation of the 90-meter (289-foot) long freeze pipes, the remaining space inside the microtunnel tubes was filled with a cement mortar. The summary parameters for this ground freezing project are:

- There were four frozen tunnel drives;
- The depth of the frozen soil top below the railroad varied from 3.7 to –7.0 meters (12 to –22.5 feet);
- The excavation zone for each tunnel drive was 100 square meters (120 square yards);
- There were 86 microtunnels, each with a

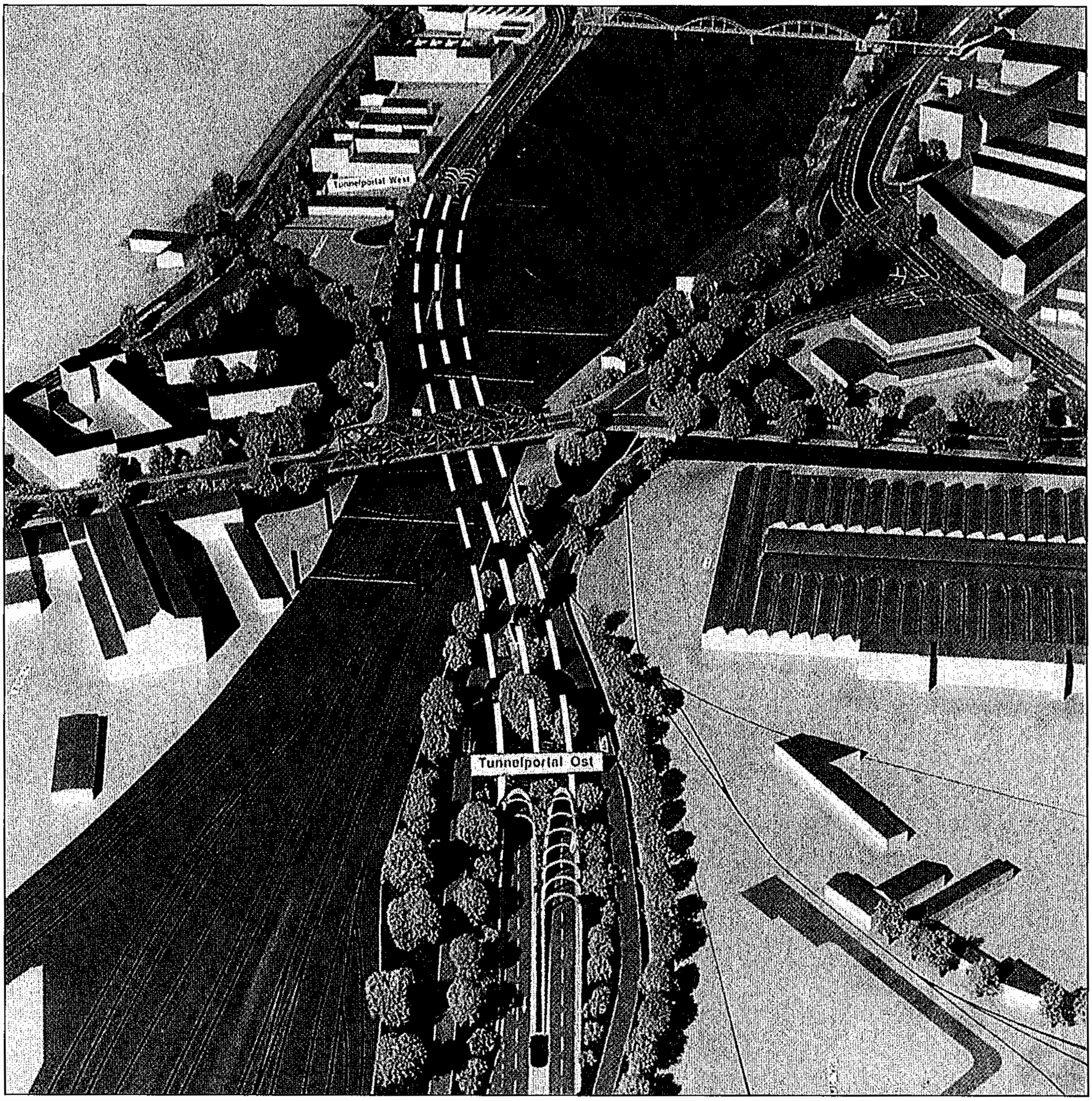

FIGURE 15. A model of the tunnel and railroad alignment for the Fahrlachtunnel project.

47 centimeter (18.5 inch) diameter, for a total length of 7,900 meters (4.8 miles);
- Total frozen soil length was 184 meters (590 feet);
- Total frozen soil volume was 27,000 cubic meters (35,313 cubic yards);
- Frozen soil thickness was 1.75 meters (5.5 feet), with a saturation of 1.0;
- Average frozen soil temperature was –10 to –12.5 degrees Centigrade (14 to 9.5 degrees Fahrenheit);
- Freezing time to closure was 30 days;
- Initial freezing time (time to freeze the soil to the required thickness) was five to eight weeks;
- Frozen ground maintenance freezing time was approximately more than four hours per day; and,
- Temperature monitoring was conducted with approximately one thermocouple per cubic meter of frozen ground, for a spacing of either 0.5 or 3.0 meters (1.5 to 9.5 feet).

For the ground freezing operation for the four tunnel drives, there was a freeze plant that

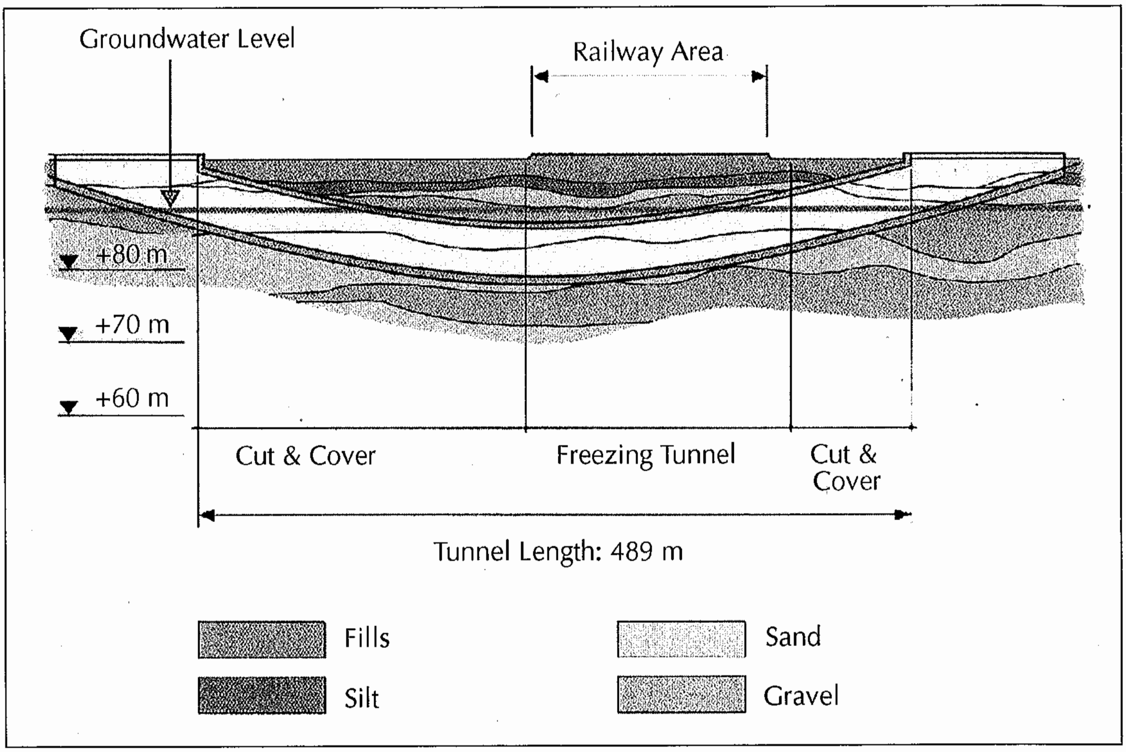

FIGURE 16. Longitudinal section of geology for the Fahrlachtunnel project.

consisted of four independent units. Operating brine temperature of the plant was –35 degrees Centigrade (–31 degrees Fahrenheit) and the plant had a total capacity of 1,680 kW. The plant was designed for the initial freezing of one 90-meter (289-foot) long tunnel drive and for the frozen ground maintenance of a second 90-meter (289-foot) tunnel drive at the same time.

During excavation, an initial shotcrete lining with a thickness of 35 centimeters (14 inches) was applied. The final concrete lining, with a thickness of 50 centimeters (20 inches), was installed in each tunnel drive after the initial lining was placed.

So far, the Fahrlachtunnel is the largest tunnel construction project that has used ground freezing worldwide. Figure 18 presents a view to the launching shaft at the south side of the tunnel.

Rehabilitation of a Jet Grouted Seal Block for Fernbahntunnel, Lot 3, in Berlin, Germany. The Fernbahntunnel Project Lot 3 consisted of construction of an underground railway with four tracks. For the tracks, four single tubes with an excavation diameter of 8.9 meters (28.5 feet) and a 7.8-meter (25-foot) inside diameter were driven using slurry shield tunnel boring machines (TBMs). The launching shaft had a length of 40 meters (128 feet), width of 60

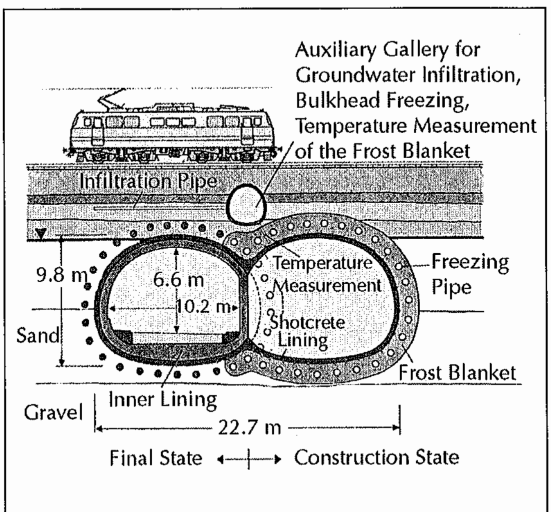

FIGURE 17. A cross-section of the Fahrlachtunnel.

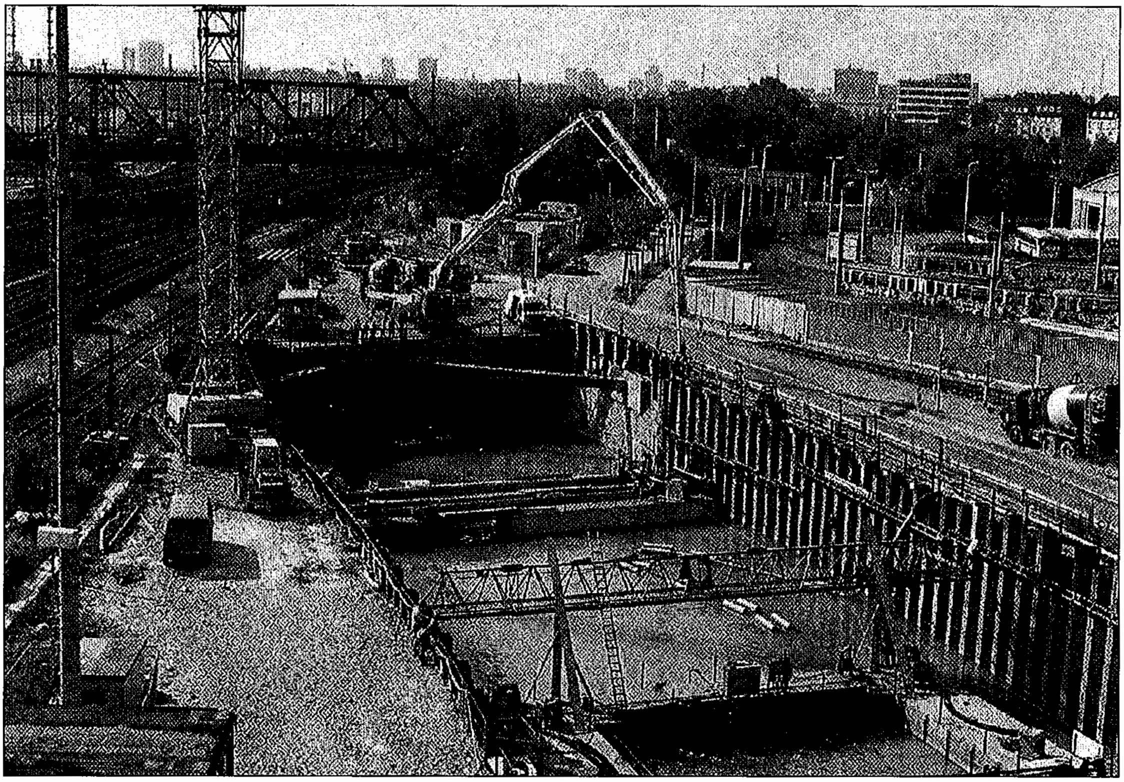

FIGURE 18. The southern side of the deep excavation for the Fahrlachtunnel.

meters (192.5 feet) and a depth of 15 meters (48 feet). It was constructed using a large caisson, which contained four openings that were temporarily plugged with non-reinforced concrete for the later launching of the four TBMs through the caisson wall. It was planned to remove the non-reinforced concrete prior to TBM installation. A jet grouted seal block was constructed after the caisson was sunk to seal the openings after the removal of the concrete. The seal block served both as a structural element (soil and water pressure) and to cut off the water.

During the removal of the concrete for the first opening, initially just water and then later large amounts of water and soil flowed into the caisson. The leakage could not be stopped and the workers had to be evacuated. The loss of soil outside of the caisson caused a sinkhole at the ground surface and the caisson finally was flooded in order to prevent more damage.

Because of the significant leakage of the seal block, and also due to the soil movement, numerous cracks in the seal block were assumed to have occurred. The decision was made to seal and strengthen the block using ground freezing. Ground freezing was selected because all existing cracks and leaks could be reached as the frost would grow in the whole block. Figure 19 shows a vertical section of the caisson and the seal block.

The undisturbed ground in the area of the caisson consisted of fine to medium sand with interbedded gravel layers a few centimeters thick over the whole depth. The groundwater level was approximately 3 meters (9.5 feet) below the surface. The existing seepage velocities were 1.5 meters (5 feet) per day and, therefore, not considered critical for ground freezing purposes.

For the remediation efforts, the thickness and the width of the seal block were enlarged with jet grouting techniques. The final total thickness was approximately 7.4 meters (24 feet) for structural and safety reasons.

The purpose of rehabilitating the seal block using ground freezing was to provide temporary groundwater cut-off and ground support

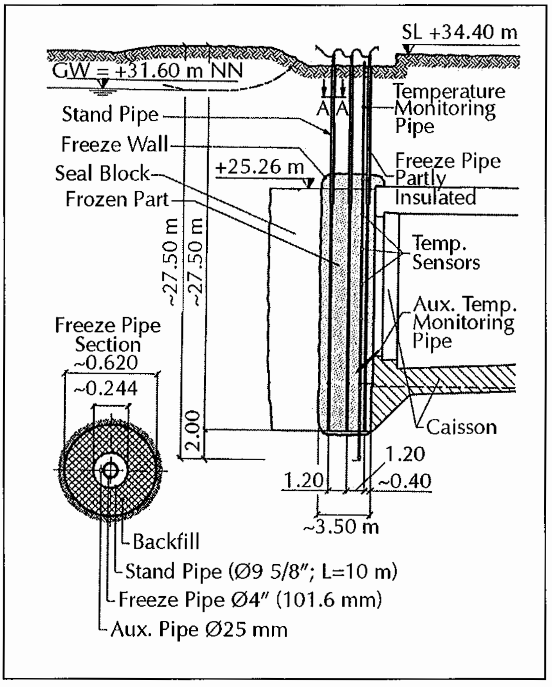

FIGURE 19. A vertical section of caisson and seal block for Fernbahntunnel Lot 3.

for the time that was needed to lower the water inside the caisson, remove the non-reinforced concrete plug and install a watertight membrane structure in the opening where the plug had been.

Based on the project's structural design, the required freeze wall thickness was 3.5 meters (11 feet). The freeze wall was width was 60 meters (192.5 feet) and its height was 16 meters (51 feet). It had a total frozen volume of 3,400 cubic meters (4,447 cubic yards). Based on thermal FE calculations, three rows of freeze pipes with the following spacings were chosen:

- Row 1 (next to the caisson): 0.9 meters (3 feet); and,
- Rows 2 & 3: 1.2 meters (4 feet).

The freeze pipe layout was required to meet the following demanding requirements for the freeze wall:

- Freeze wall temperature of ≤ –10 degrees Centigrade (14 degrees Fahrenheit);
- Outer edge temperature of ≤ –2 degrees Centigrade (28 degrees Fahrenheit); and,

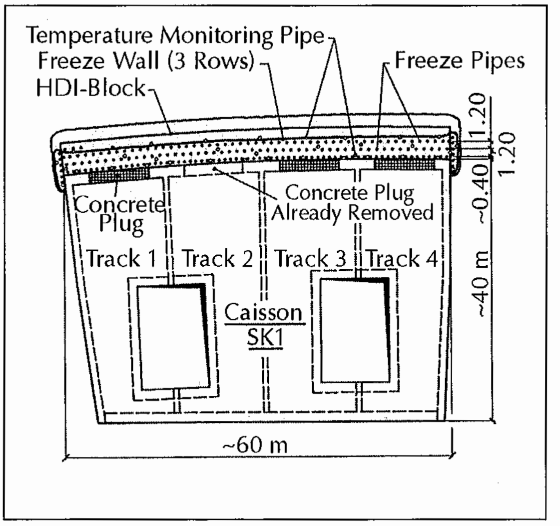

FIGURE 20. Top view and freeze pipe layout for Fernbahntunnel Lot 3.

- Temperature at the caisson interface of more than –10 and less than –20 degrees Centigrade (14 and –4 degrees Fahrenheit).

The last requirement was necessary to limit the temperature-induced stresses in the concrete of the caisson wall. Figure 20 shows a top view of the caisson with the freeze pipe layout.

Following are the parameters for the freeze system used for this project:

- Total of 184 freeze pipes in three rows — 66 in Row 1 and 50 each in Rows 2 and 3 (see Figure 21);
- Seven freeze pipes at the side;
- 35 temperature monitoring pipes;
- Six to ten thermocouples per monitoring pipe;
- A total of 350 thermocouples to monitor the ground and brine temperatures;
- Total freeze plant capacity of 465 KW at –35 degrees Centigrade (–31 degrees Fahrenheit);
- Cooling agent was $CaCl_2$ brine (30 percent);
- Freeze-up time for first section (Openings 1 and 2) to meet all design requirements was approximately five weeks, although an additional two weeks of freezing was required by the owner;

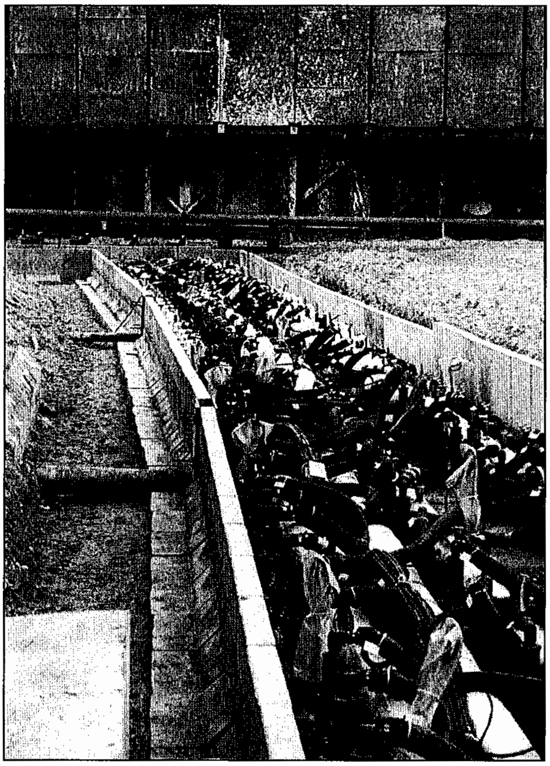

FIGURE 21. Freeze pipe header, supply and return lines on Fernbahntunnel Lot 3.

- Freeze-up time for second section (Openings 3 and 4) was about four and a half weeks (time was reduced due to pre-cooling from the adjacent section); and,
- Freeze wall maintenance phase in both sections was about six to ten hours of freeze time per day.

After removing the concrete plug, a special watertight membrane structure (developed by the main contractor) was installed under the protection of the freeze wall at each opening. This structure consisted of a circular steel ring that was attached to the edge of the opening, and a rubber membrane that spanned over the entire opening. Bentonite mud filled the space between the membrane and the frozen ground. Once a steady pressure on the mud was created, the freezing operation was turned off for that opening. Figure 22 shows the freeze wall after the removal of the concrete plug and prior to membrane installation. The membrane could be dismantled and removed after the TBM was installed in the launch ring and the chamber in front of the cutting wheel was pressurized by compressed air.

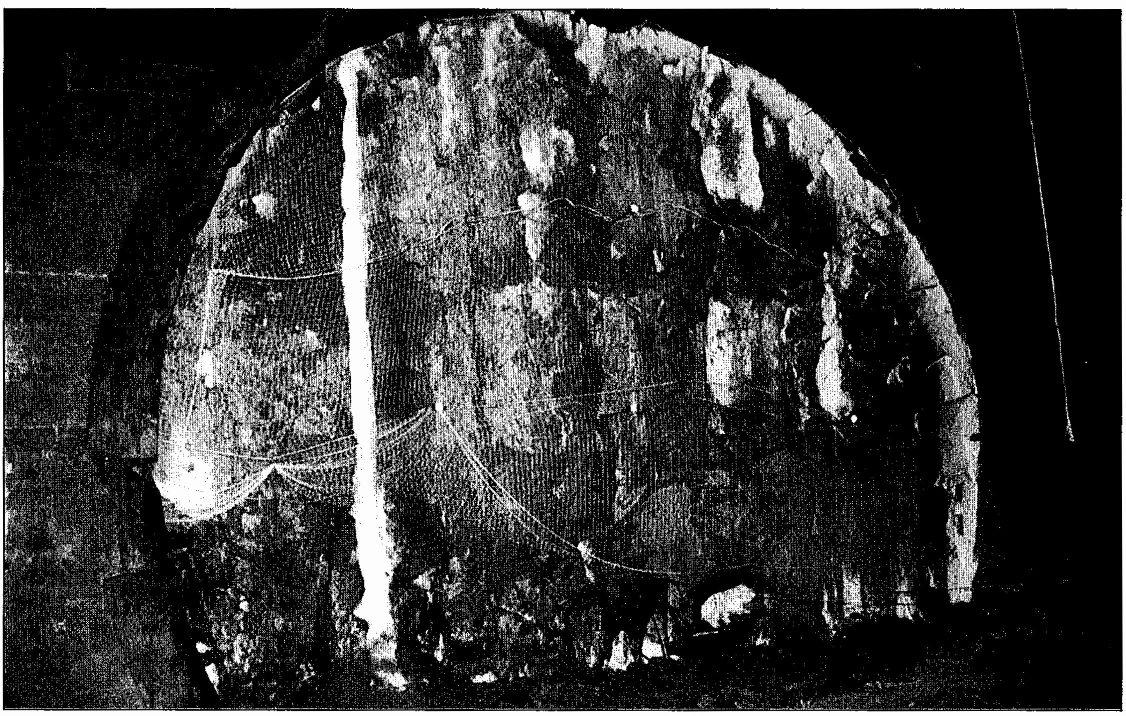

FIGURE 22. Freeze wall exposed after the removal of the concrete plug.

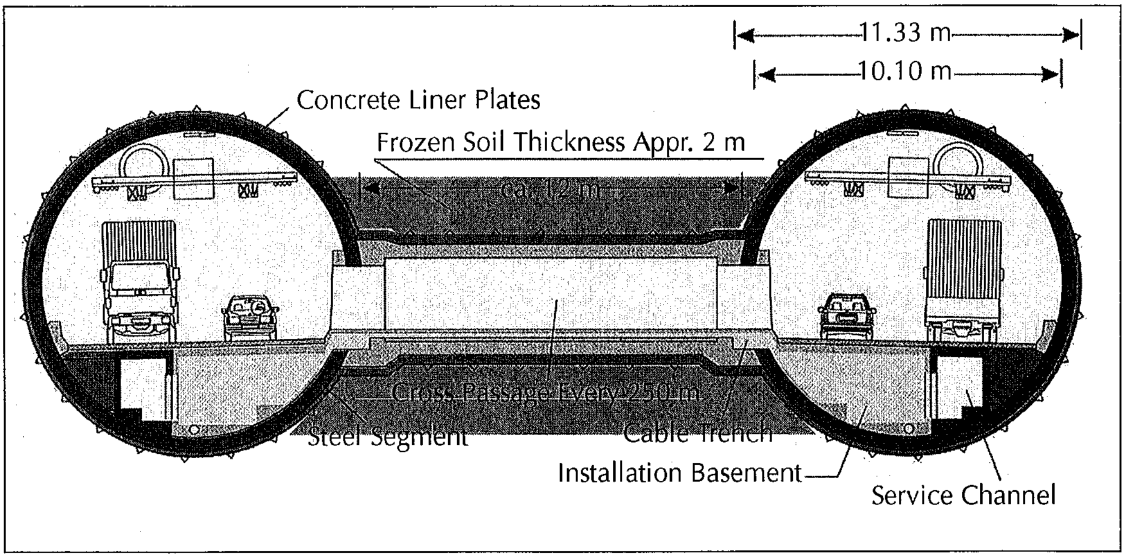

FIGURE 23. Section in the area of a cross-passage for the Westerscheldetunnel.

Prior to launching the air-pressurized hydro-shield TBMs, all freeze pipes had to be removed and the holes had to be backfilled with grout in order to prevent the sudden loss of pressure in the chamber in front of the cutting wheel during drive of the TBM through the seal block. Therefore, the freeze pipes were heated until the ground temperature was approximately +2 degrees Centigrade (35 degrees Fahrenheit).

All line connections were changed from the freeze plant to a heat plant, which consisted of two electrical immersion type heaters with a total capacity of 150 kW. The heated brine temperature was +30 degrees Centigrade (86 degrees Fahrenheit). It took approximately 33 days to heat up the ground as required. In the end, all pipes were extracted except one, which was removed by being overdrilled.

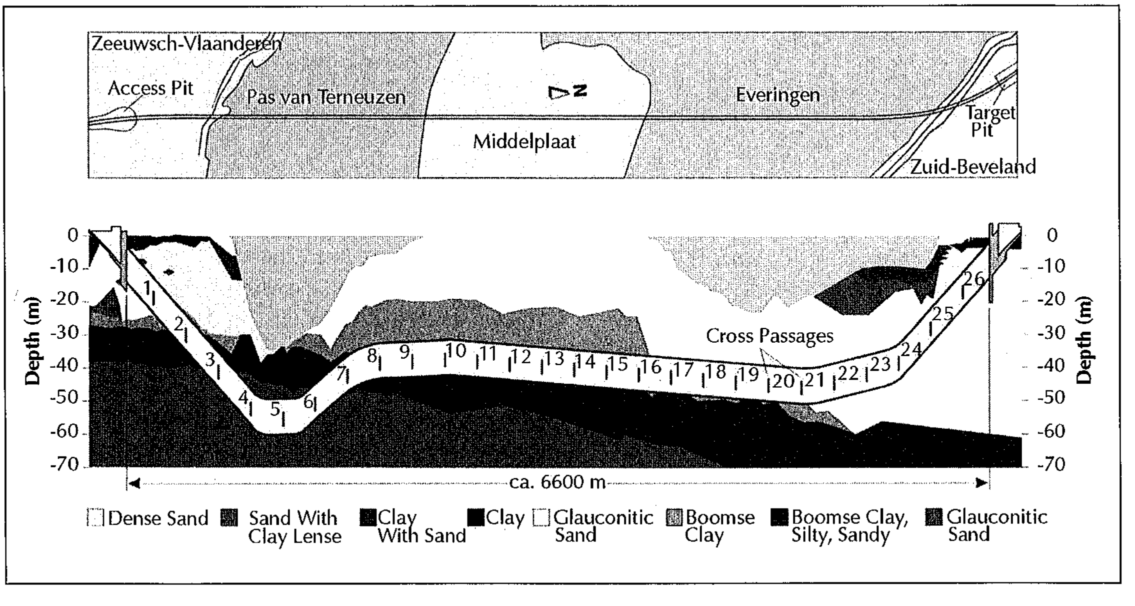

FIGURE 24. Longitudinal section and geology for the Westerscheldetunnel project.

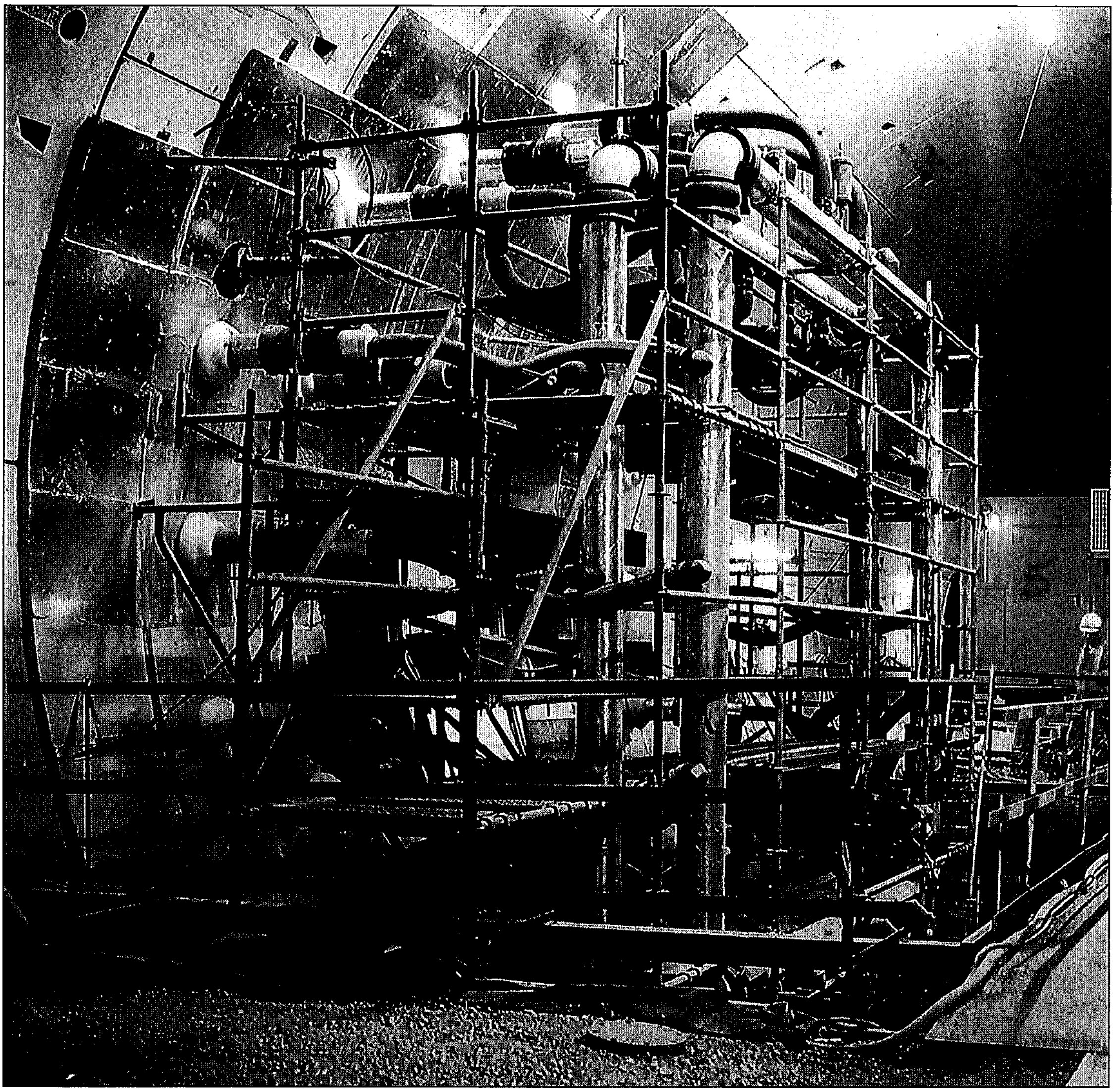

FIGURE 25. Main tunnel with installed freeze pipes for the cross-passage for the Westerscheldetunnel.

Westerscheldetunnel, Terneuzen, the Netherlands. Located in the western part of the Netherlands, the Westerscheldetunnel connects Zeeusch-Vlaanderen with Zuid Beveland on the continent. The tunnel project consisted of two tubes, with each tube containing two road lanes. The tunnel tubes were driven under the North Sea using two TBMs with a pressure-balanced hydro-shield. The bore diameter of the tunnels was 11.33 meters (36 feet). Each tunnel tube had a length of 6.6 kilometers (4 miles) and the lowest elevation was approximately 60 meters (192.5 feet) below mean sea level.

For safety requirements, the tunnels were connected by cross-passages every 250 meters (802 feet). A total of 26 passages with a clear cross-section of 6.25 square meters (7.5 square yards) and an average length of 12 meters (38.5 feet) were built (see Figure 23). The passages were constructed under the temporary protection of a watertight and structural frozen soil body. The excavation for the cross-passages was done using NATM.

The individual passages were located in both cohesive and non-cohesive soils. The general soil profile consisted of 20 to 30 meters

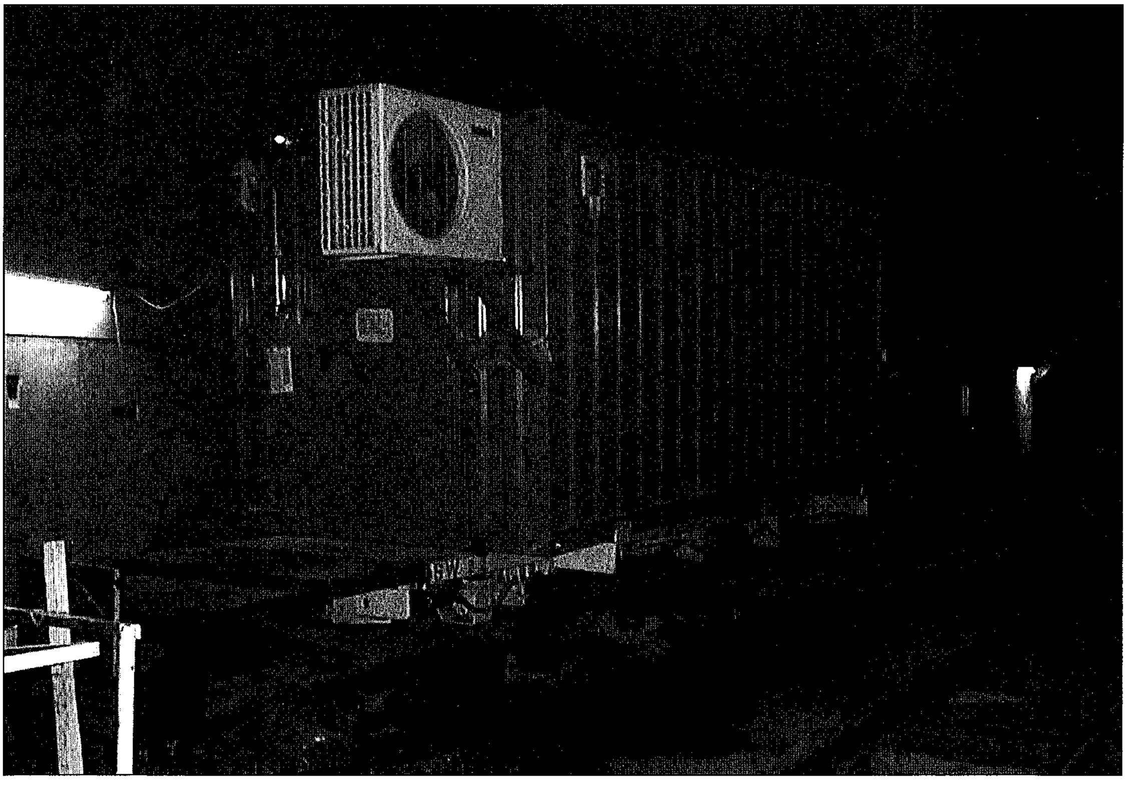

FIGURE 26. Freeze unit inside the Westerscheldetunnel.

(64 to 96 feet) of medium dense sand with embedded layers of clay, peat and sea silt. Underlying this stratum was stiff clay 8 to 28 meters (25 to 90 feet) thick. Below the clay was very dense sand that was hydraulically connected to the upper medium dense sand and the seawater level. As a result, water pressures of 6.5 bars at tunnel depth had to be considered for the design and construction (see Figure 24).

In addition to available soil data provided by the owner, further soil investigations and lab testing were conducted that focussed on determining the soil properties and behavior once the soil was frozen and after it had thawed.

Each cross-passage freeze zone consisted of 22 freeze pipes and two temperature monitoring pipes. The freeze pipes were located around the excavation line as shown in Figure 25.

A major construction problem that was encountered during the installation of the freeze pipes was extremely high water pressure. To accommodate the high pressure, a special sleeve was designed for the freeze pipes. The borings were drilled from the eastern tunnel tube to the western tube, using a specially enhanced lost bit drilling technique.

For the ground freezing operation of each cross-passage, a freeze unit with an operating brine temperature of –37 degrees Centigrade (–35 degrees Fahrenheit) and a capacity of 94 kW capacity was used. The freeze unit was located inside the launching tunnel tube directly beside the cross-passages in order to avoid long conduits that would cause heat losses (see Figure 26).

Difficulties in achieving complete closure of the frozen soil at the interface of the cross-passage and the receiving tunnel lining were recognized during the drilling of the first cross-passage. The problem occurred due to a modification in a part of the tunnel where steel lining segments were used. The steel lining at the cross-passage interface resulted in a larger heat transfer than was originally anticipated.

In the parts where the frozen soil body was connected to reinforced concrete lining seg-

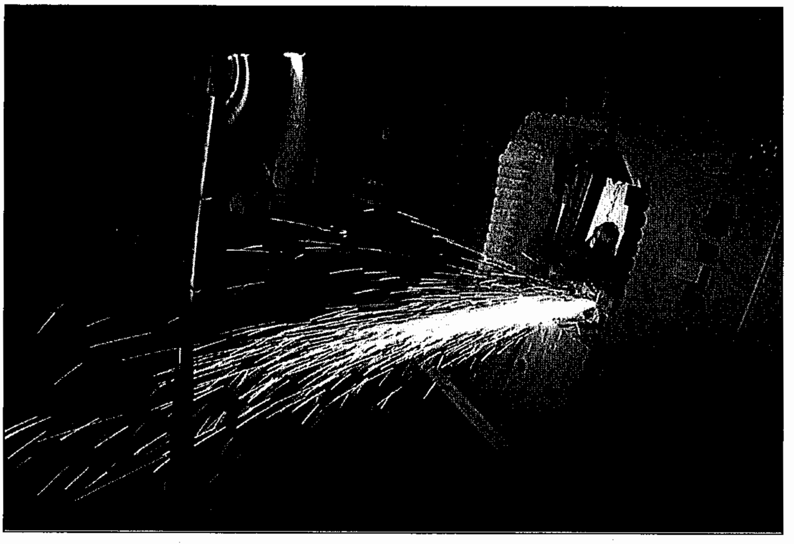

FIGURE 27. Cross-passage opening inside a Botlekspoortunnel tube.

ments no problems occurred. However, innovative methods to attain the proper freeze temperatures were needed. For the first cross-passage, dry-ice was used to cool down the steel lining elements at the receiving tunnel. Doing so resulted in an effective closure.

For the remaining cross-passages, a temporary curtain around the steel lining segments was installed. Inside the curtain room the air was cooled down using a special air-conditioning unit. Closure was achieved in every case without problem.

Botlekspoortunnel, Rotterdam, the Netherlands. The Botlekspoortunnel is part of the Betuweroute, a double-track freight train route, that links the harbor of Rotterdam with the European mainland. The project is considered one of the biggest infrastructure projects in the Netherlands. The Betuweroute is 160

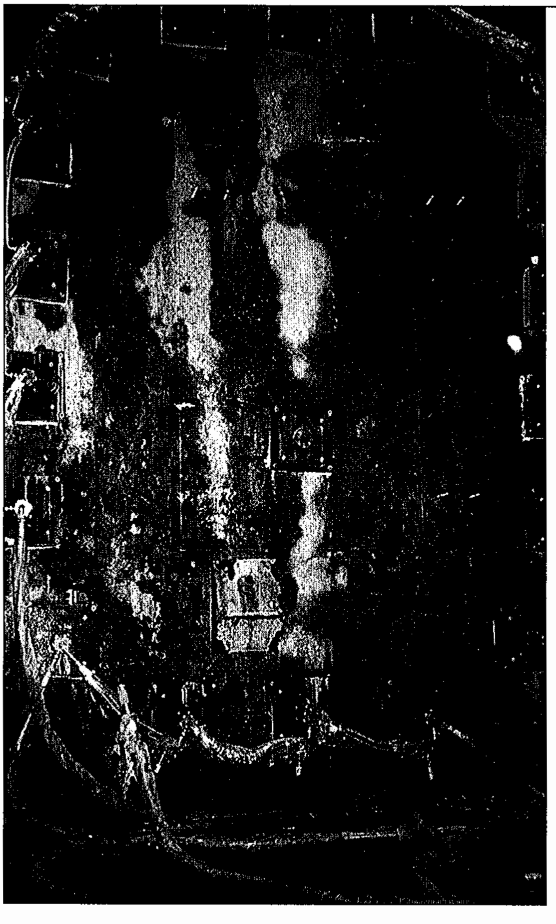

FIGURE 28. Freeze pipes inside the deep shaft for the Botlekspoortunnel.

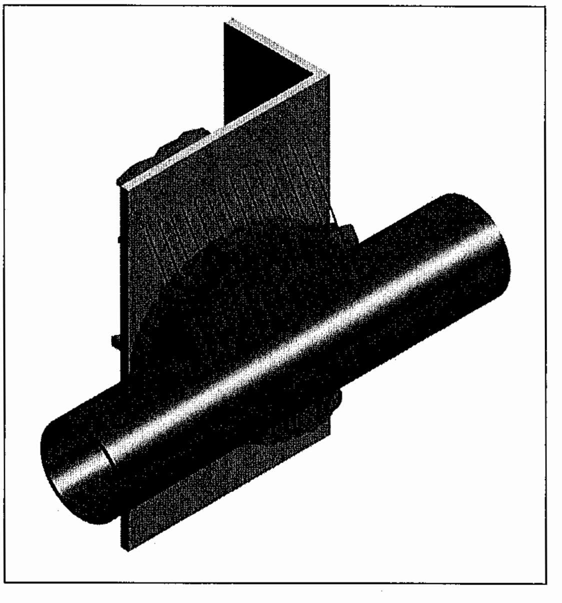

FIGURE 29. A model of the cross-passage between the shaft and tunnel tube for the North-South City Train Line, Cologne.

kilometers (97 miles) long and requires an investment of approximately 4 billion euros.

The Botlekspoortunnel is a double-track tunnel and is the first railway tunnel in the Netherlands that was built using a pressure-balanced hydro-shield. In total, it is 3,400 meters (2 miles) long — 1,850 meters (5,935 feet) were built by shield driving.

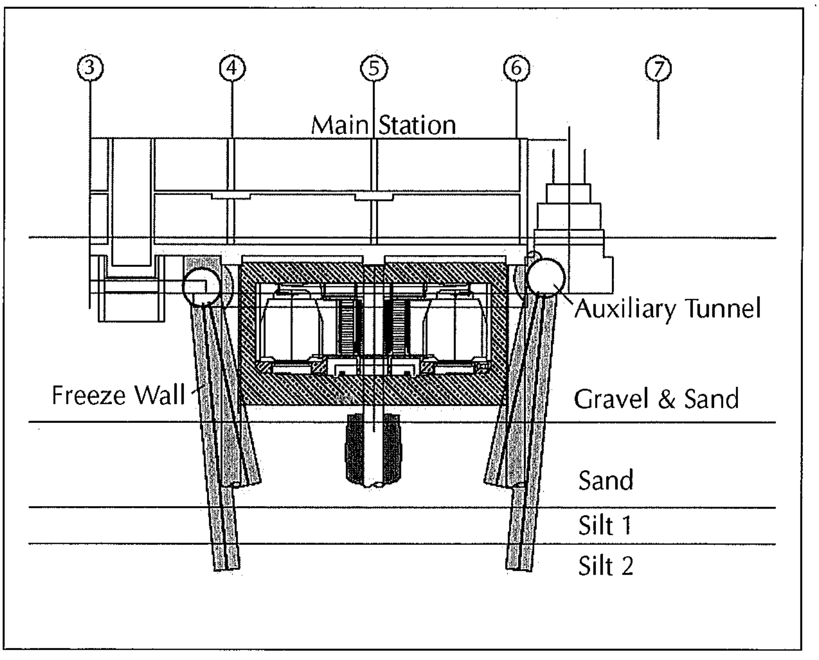

FIGURE 30. The deep excavation underneath a main station in Leipzig, Germany, using ground freezing.

For safety requirements, the tunnel tubes had to be connected by three cross-passages in the area of Rotterdam. These cross-passages were also built using the ground freezing method. But, in contrast to the Westerscheldetunnel, an additional deep diaphragm concrete wall shaft was built in the middle between the tunnel tubes. Once that shaft was built, freeze pipe drilling was conducted from both sides of the shaft to the adjacent tunnel tube.

Because of that shaft, the freeze pipes were very short; most had lengths of less than 2 meters (6.5 feet). Since the volume of the frozen soil was relatively small, the liquid nitrogen freezing method was chosen. The cross-passages were driven using the mining method, starting from the sinking shafts to both tunnel tubes.

The cross-passages were at a depth of approximately 25 meters (80 feet) below the ground surface and the groundwater level. The individual passages were mainly located in non-cohesive soils (medium to very dense sands). Only small parts of cohesive layers were present in the area of ground freezing.

The freeze-up of the frozen soil body to the required thickness of 1.5 meters (5 feet) took only one week due to the use of liquid nitrogen. Figure 27 shows the opening of the cross-passage inside a tunnel tube when the excavation from the shaft was finished. The frozen soil body served both as a structural element (soil and water pressure) and to cut off the water. Figure 28 shows the freeze pipe layout from inside the deep shaft.

Current Projects

The following projects that utilize the ground freezing method are currently under construction or are planned for construction, or have been recently finished:

- Marienplatz, Munich, Germany — The expansion of an existing underground subway station underneath the city hall consists of two freezing sections each 100 meters (320 feet) long. Currently finished.
- Subway Vienna, Austria — Undercrossing the Danube canal, length approximately 70 meters (225 feet). Freezing operation started in 2005.
- U5 Shuttle — Underground station Brandenburger Tor Subway line U5, in Berlin, Germany. Construction of an underground station using SEM under the protection of frozen soil. Freezing operation started at the end of 2005.

- North-South City Train Line, Cologne, Germany — Construction of one large tunnel section (switching station), one large section of an underground station and several cross-passages (see Figure 29). Freezing operations start 2006/2007.
- Randstad Rail Rotterdam, The Netherlands — Construction of five cross-passages between two TBM-driven tunnel tubes. Freezing operation starts 2006/2007.
- Hubertustunnel Den Haag, The Netherlands — Construction of five cross-passages between two TBM-driven tunnel tubes. Freezing operation starts 2006/2007.
- Airport-City Train, Hamburg, Germany — Construction of four cross-connections between two caissons and two TBM-driven tunnel tubes. Freezing operation started in 2005.
- Central Station, Rotterdam, the Netherlands — Large and deep excavation at a main station highly frequented by traffic and pedestrians, combining concrete diaphragm walls and freeze walls.
- City Tunnel, Leipzig, Germany — Undercutting of an old main station (see Figure 30) for the construction of a two-track city train line with excavation underneath an existing old main station 16 meters (51 feet) deep, using frozen retaining walls (structural and water cut-off). Length approximately 80 meters (257 feet). Currently being planned.

Summary

In many cases, ground freezing is the only solution to create a watertight and load-carrying soil body in water-bearing soil. However, numerous other applications are possible and cost-effective solutions can be realized even under highly demanding conditions. Ground freezing has become more popular and is going to be used more frequently in the future. Its use, in particular, in tight, conjested urban environments is increasing. Essentially, ground freezing is a very safe method but it has to be designed by engineers who are experienced with ground freezing and who use sound principles. In addition, it is important that the ground freezing operation must be monitored throughout the construction process to assure safety.

NOTE — *This article is based in part on a presentation given in March 2000 to the BSCES Geotechnical Group.*

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