Ground Freezing
The ground freezing process converts pore water into ice by the continuous circulation of a cryogenic fluid within a system of small diameter, closed-end pipes installed in a pattern consistent with the shape of the area to be treated. The frozen pore water acts as a bonding agent, fusing together particles of soil or rock to significantly increase compressive strength and impart impermeability.

Freeze pipes are typically installed vertically in the soil and connected in series-parallel. The coolant is pumped down a drop tube to the bottom of the freeze pipe and flows up the annulus, withdrawing heat from the surrounding soil. When the soil temperature reaches 32°F (0°C), ice begins to form around the pipes in the shape of vertical, elliptical cylinders. As the cylinders gradually enlarge with time, they interconnect to form a continuous wall. Once the frozen wall reaches design thickness, the freeze plant is typically operated at a reduced rate to maintain the condition.

Unlike other groundwater cut-off and excavation support techniques, ground freezing is a minimally invasive technique that requires only limited physical penetration into the ground and propagates thermally, rather than by displacement. The ground remains largely undisturbed during freeze pipe installation and the freezing process and, in most instances, reverts to its original state once freezing is discontinued.

Artificial ground freezing was the brainchild of German scientist F. Hermann Poetsch, who first patented his “Method of and Apparatus for Sinking Shafts through Quicksand” in 1883. Its first use in the United States was for the Chapin Mine Company in Iron Mountain, MO, where freezing was performed to a depth of 100 feet.

The technique met with great success throughout Europe, and became relatively common where the project could bear the cost of constructing the massive refrigeration plant required. However, it would be more than 60 years before the second U.S. ground freezing application was completed to aid the sinking of a 765-feet deep shaft at the Potash Company of America’s Carlsbad, NM mine.

These days, ground freezing is common worldwide and its use has extended to encompass a range of civil and environmental applications. However, providing groundwater control and excavation support for shaft sinking remains the primary application. In fact, for deep shafts, no better method has yet been established.

### Conditions Where Ground Freezing is Most Cost Effective

- Ground where penetrability by drilling, jet grouting, clamshell excavation, or other vertical cut-off tools is limited.
- Filled ground and ground containing man-made obstructions.
- Virgin ground containing cobbles, boulders, or an irregular soil/rock interface.
- Ground that has been disturbed due to unstable conditions or water inflow.
Brine Freezing
Brine freezing is typically used for large, longer-term applications where project schedule permits a freeze formation period measured in weeks and months.

Chilled calcium chloride brine is the most common cooling agent. It is cooled typically to temperatures between -15°C and -25°C (5°F and -13°F) and pumped down a drop tube to the bottom of the freeze pipe, then flows up the annulus, withdrawing heat from the soil. Typically, the freeze pipes are hooked up in series–parallel. The brine is returned to the refrigeration plant, where it is chilled and recirculated.

Refrigeration plants can be regulated to re-circulate brine over a relatively wide and controllable range down to approximately -35°C (-31°F). With proper placement of the freeze pipes and careful design of the brine delivery piping, a brine freeze will provide relatively even and consistent cooling effort in the ground. Typically, the cooler temperatures are desirable for freeze formation and warmer temperatures are desirable for maintenance of the freeze.

Soils Suitable for Ground Freezing
Ground freezing can be accomplished in all soils and in pervious or fissured rock, and is cost-effective where both support of excavation and groundwater cut-off are required and the ground improvement must be provided at significant depth. However, its applicability and cost effectiveness increases in difficult, disturbed or sensitive ground.

Liquid Nitrogen Freezing
Liquid nitrogen, which acts more quickly than brine, has been used effectively for emergency situations in disturbed, displaced, and loose ground conditions where detailed soil delineation cannot practically be performed in a timely manner, and on smaller projects such as where the freeze is required to be maintained for a short period of time. Although the per-day cost is greater than with circulated brine, the accelerated freeze formation time makes this method very competitive.

The liquid nitrogen is stored in an insulated pressure vessel, which is refilled periodically from special over-the-road tank trucks. The liquid is conducted to the drop tube in the freeze pipe, boils rapidly, and the exhaust gas is vented to the atmosphere. At the point of application, the liquid boils at 196°C (-320ºF). Because of the extremely low temperature, freezing with liquid nitrogen is rapid and high strengths of frozen soils can be achieved.

Types of Ground Freezing

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Peripheral Freezing
The general intent of the creation of a frozen containment structure, or peripheral freezing, is to minimize the amount of frozen ground to be excavated. The frozen wall, of appropriate thickness and strength, is constructed primarily outside of the excavation limits but terminates a short distance inside the future excavation surface so that the freshly exposed face remains frozen and may be insulated before significant melting begins.

Vertical peripheral freezing for excavation support and groundwater control during deep shaft construction is the primary application, with numerous projects completed across North America. Other tunneling related applications include horizontal peripheral freezes for sewer and utility line installations, and frozen-arch canopies to prevent ground loss or mitigate settlement during excavation.

Mass Freezing
Under certain circumstances, it may be desirable to completely freeze large volumes of soil. Such mass freezing may be justified where:

- A more homogenous ground condition is desired, such as to permit a hard rock TBM to pass through a mixed ground condition.
- Ground control in difficult subsurface conditions is crucial to the success of a project.
- The excavation of frozen ground provides a greater degree of overall safety of the operation.
- No geologic cutoff is present within reasonable depth below subgrade at a proposed shaft location. In this case, the use of ground freezing may necessitate a mass freeze to create an artificial bottom seal.
- Limited cover or sensitive structures warrants improvement of the ground outside the tunnel.

The unprecedented use of mass ground freezing to stabilize Boston’s historic soils allowed safe jacking of three massive box tunnels immediately beneath rail lines serving South Street Station during Boston’s Central Artery/Tunnel (Big Dig) megaproject. Freeze system installation and operation, and tunnel jacking, was accomplished with no interruption to train schedules.
Advantages of Ground Freezing Unique to the Construction of Shafts

► The freeze can be implemented through the soil/rock interface, which is often the most difficult geology in which to create a groundwater cut-off by other methods.
► A frozen wall, by design, is continuous into the underlying cut-off and resists the loads imposed by full groundwater and soil pressures.
► Proper instrumentation can provide assurance of the integrity of the freeze prior to excavation.

During construction of the 13-mile long Brightwater Tunnel in King County, WA, ground freezing to a depth of 240 feet was deemed the best option for sinking of a 32-foot diameter access shaft through a highly complex and challenging soil profile with a high groundwater level.

Additional borings taken during construction of New York City's No. 7 Line Extension revealed rock cover of only five feet above the crown and west wall of the south end tail tunnel. Mechanical excavation, which replaced the original drill and blast techniques, could not safely take place unless the envelope of saturated, weathered rock and overburden above the tunnel crown was improved. Ground freezing was selected as the safest and most assured method of achieving this.
Environmental Remediation

Nowadays, ground is an accepted tool for environmental clean-up and for containment of contaminants on civil and urban sites.

Installation of the frozen wall creates minimum disturbance to the in situ soil and essentially eliminates the need to pump contaminated groundwater. Production of solid waste that must be disposed of is minimal. Also, there is negligible change in the groundwater regime outside the confined area following thawing of the freeze.

In highly contaminated site conditions, the frozen wall can provide both containment and earth support for the excavation and removal of contaminated soil.

Effective groundwater control is typically of high priority where environmental clean-up below the water table is required. Installation of a perimeter wall of frozen ground around the problem area completely isolates the groundwater contained within, which can then be pumped and treated. Because the frozen wall is continuous, the potential for leakage through joints or panels, such as can occur with structural containment methods, is eliminated.

At the Fulton Terminals Superfund Site in New York, an elliptical frozen earth cofferdam was installed to bedrock at 65 feet below working grade to permit excavation and removal of contaminated soils.

Quality Control With Ground Freezing

The satisfactory performance of the freeze depends on the maintenance of strict quality control measures throughout installation and operation of the ground freezing system, including:

Surveying of every borehole to verify borehole deviation that can result in “windows” or zones of frozen earth of less than design thickness.

Installation of ground temperature monitors in strategic monitoring boreholes to confirm adequate freeze propagation.

Installation of piezometers inside and outside the frozen zone to measure groundwater gradients. In conjunction with relief wells, piezometers confirm isolation of the groundwater inside the frozen zone from groundwater outside the frozen zone, indicating closure of the freeze.

Monitoring of brine temperatures to confirm proper output from the freeze plant and heat extraction from the ground.

Data acquisition and analysis to track the rate of growth of the freeze.
Moretrench added ground freezing to its geotechnical repertoire in 1976. Since then, the company has completed numerous complex projects nationwide to meet a diverse range of challenges, including these:

**Central Artery/Tunnel, Boston, MA**
In the largest project of its kind ever undertaken in the USA, mass freezing stabilized complex, obstruction-laden soils for jacking of three, massive box tunnels beneath live rail tracks for the I-90/92 approach to the Fort Point Channel crossing.

**City Water Tunnel No. 3, New York, NY**
Brine freezing to depths ranging between 75 and 130 feet from ground surface, for construction of deep, vertical access shafts rising through glacial deposits and water-bearing sands above bedrock. Scheduled to be completed in 2020, City Water Tunnel No. 3 will eventually span more than 60 miles, and represents the largest capital construction project in New York City's history.

**Strategic Petroleum Reserve, Weeks Island, LA**
Brine freezing to prevent further erosion caused by groundwater inflow into an underground salt cavern housing 2.1 billion gallons of crude oil. Freezing was maintained for the five years required to remove the oil and close the site.

**2nd Avenue Subway, New York, NY**
Brine freezing to provide ground stabilization and water cut-off where borings had indicated mixed face soil/rock conditions and inadequate rock cover above the crown of a section of twin, 22-foot diameter subway tunnels being mined primarily through rock.