Ground Stabilization for Urban Tunneling

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In dense, urban areas, the need for soil stabilization often goes hand-in-hand with soft ground tunneling operations and related shaft construction. Hard rock tunneling can also be problematic in areas of the tunnel alignment where cover is insufficient or the rock itself is potentially unstable.

While some challenges, such as foundation protection, can be anticipated and prepared for, other problems may become apparent only during preparatory works or the tunneling process itself. This is especially true in areas where the subsurface profile is complex, where overlying structures are intertwined with the new construction and accurate information on the condition and location of their foundation systems is not available, or where difficult subsurface conditions such as uncontrolled fill, man-made obstructions, or boulders may impact shaft or cut-and-cover excavation support systems or the tunneling itself.

Specialty geotechnical contractors have several ground improvement tools at their disposal to resolve soil and rock related tunneling project issues. Grouting systems represent the most versatile of these, allowing the contractor to develop and implement the most appropriate stabilization or settlement control solution that is targeted to the subsurface conditions and surrounding structures and meets the project requirements.

Ground freezing is also well-suited to soil stabilization for tunneling applications, particularly where the greatest degree of assurance is required, both support of excavation and groundwater cut-off are necessary, and the improvement must be provided at significant depth or in difficult or disturbed ground.

Although more than one geotechnical approach may be technically feasible on a given project, over time some techniques, as discussed below, have emerged as textbook applications for frequently encountered soil and rock stabilization challenges.

**Mixed Face Tunneling**
Modifying the ground by jet grouting or ground freezing in order to create a homogeneous tunneling profile is proven to be effective in overcoming the problems of groundwater control, potential soil loss, maintaining alignment, and controlling running soils that are inherent in tunneling through mixed-face conditions. Both techniques create improved ground with a high compressive strength.

Jet grouting uses high-pressure, high-velocity jets to hydraulically erode, mix and partially replace the in situ soil or weak rock with cementitious grout slurry to create an engineered soil-cement product of high strength and low permeability. Jet grouting can be performed above or below the water table and in most subsurface stratigraphy from cohesionless soils to plastic clays.

The ground freezing process converts in situ pore water to ice through the circulation of a chilled liquid via a system of small-diameter pipes placed in drilled holes. The ice acts to fuse the soil or rock particles together, creating a frozen mass of improved compressive strength and impermeability, presenting a fully stabilized soil face against which the lining can be directly placed concurrent with advance of excavation.

**Shallow Cover Rock Tunneling**
Where there is insufficient rock cover above the tunnel crown and the rock itself is fractured, consolidation grouting using cementitious grouts is performed through closely spaced grout holes oriented to optimize the intersection of joints and improve the overall stability of the rock. Jet grouting or ground freezing may be used as supplements to the rock grouting program if the soil above the rock is insufficiently consolidated.

Traditional borings and horizontal borings taken from inside the 1.5-mile extension of the Metropolitan Transportation Authority's No. 7 Line indicated that the limited rock cover present as the TBM approached the receiving shaft, located in the basement of the NYC bus terminal, was tightly fractured, and that roof stability could become an issue. Microfine cement grouting conducted through an array of vertical holes drilled from inside the bus terminal stabilized the fractured rock in preparation for the TBM passing.

**Settlement Control**
Whether structural settlement is anticipated or an unexpected consequence of construction, grouting is effective in resolving the problem.
In cases where settlement is anticipated, compensation grouting has the specific design intent of providing controlled volume injections to compensate for lost ground and even induce small amounts of ground heave to correct for structural settlement. This technique, frequently used in Europe, is being increasingly employed as a preventative measure during soft-ground tunneling operations, deep excavations, or other such instances where ground loss is anticipated. The ground is intentionally fractured by the high-pressure injection of cement-based grout through sleeve port pipes to form interfused lenses or veins of grout in order to provide ground "stiffening" and even some consolidation of the soil. Grouting is typically performed in several phases, with repeat injections at each sleeve port to ensure the formation of multiple fractures through the soil.

Structures founded on spread footings or rubble foundations are particularly vulnerable to settlement. Should unanticipated ground loss occur along the tunnel alignment or during preparatory works, compaction grouting targeted to the soils beneath foundations can arrest or reduce settlement. This method is generally preferred in highly disturbed ground as it is more aggressive and provides a faster solution to inject volume and re-consolidate the disturbed soils. With compaction grouting, a relatively stiff, low-slump, mortar-like grout is injected under pressure. The grout does not permeate the soil matrix but rather forms a bulbous cement mass which will displace and densify the surrounding soil. It is possible to lift or jack structures using compaction grouting. However, repeat injections are not as readily performed as with fracture (compensation) grouting through sleeve port pipes.

Compaction grouting can also be performed as the tunnel shield passes below to control ground movement and thus protect overlying structures. Pioneered on the Bolton Hill Tunnel in Baltimore in the late 1970s, this approach was recently used in Pittsburgh during construction of the twin-tunnel North Shore Connector to protect a historically significant structure founded on shallow footings.

Potential Running Soils
As an excavation pre-support method, sodium silicate permeation grouting has been widely used to improve the strength and cohesion of granular soils prior to tunneling and underground construction and is equally applicable for NATM, hand-mined, or open-face bored tunnels.

The technique is typically defined as the flow of a low-viscosity grout into the pores of the soil without displacing or changing the soil structure. The characteristics of the ground are modified with the hardening or gelling of the grout. Controlled and accurate grout placement is achieved through the use of sleeve port pipes which can be installed vertically, at an angle, or horizontally. While vertical or inclined grouting is most common, horizontal pipe installation may be required to allow grouting to take place where surface access is prohibited or limited, such as beneath heavily travelled highways or designated historic areas.

Tunnel Eye Stabilization
Tunneling through running soils or below the water table has the potential to lead to unacceptable ground loss during cutting of the "eye" for TBM or MTBM launch and retrieval. Both permeation grouting and jet grouting are effective in providing a stabilized soil zone behind launch and retrieval pit excavation support to allow the eye to be cut out of the excavation support system. Ground freezing, using brine or liquid nitrogen as the cooling agent depending on the required duration, may also be used.

Deep Shaft Construction
Where the construction of deep shafts is required through difficult soil conditions, ground freezing as a temporary ground improvement method provides both water cut-off and excavation support. This technique can be employed on sites with limited/restricted access with minimal spoils generation.

Scheduled for completion in 2020, New York City's Water Tunnel No. 3 is being mined through metamorphic granite deep underground. Many of its access shafts must extend through glacial deposits and water-bearing sands that lay above the rock. Ground freezing of the overburden to depths well in excess of 100 ft has been used to provide the needed excavation support and groundwater control at a number of shaft locations. For shallower, less problematic soils, jet grouting may be considered.

Grouting and ground freezing programs are effective problem-solvers for tunneling and related works. However, these are highly specialized techniques and their application requires the expertise of an experienced geotechnical engineer working hand-in-hand with a qualified geotechnical contractor.

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