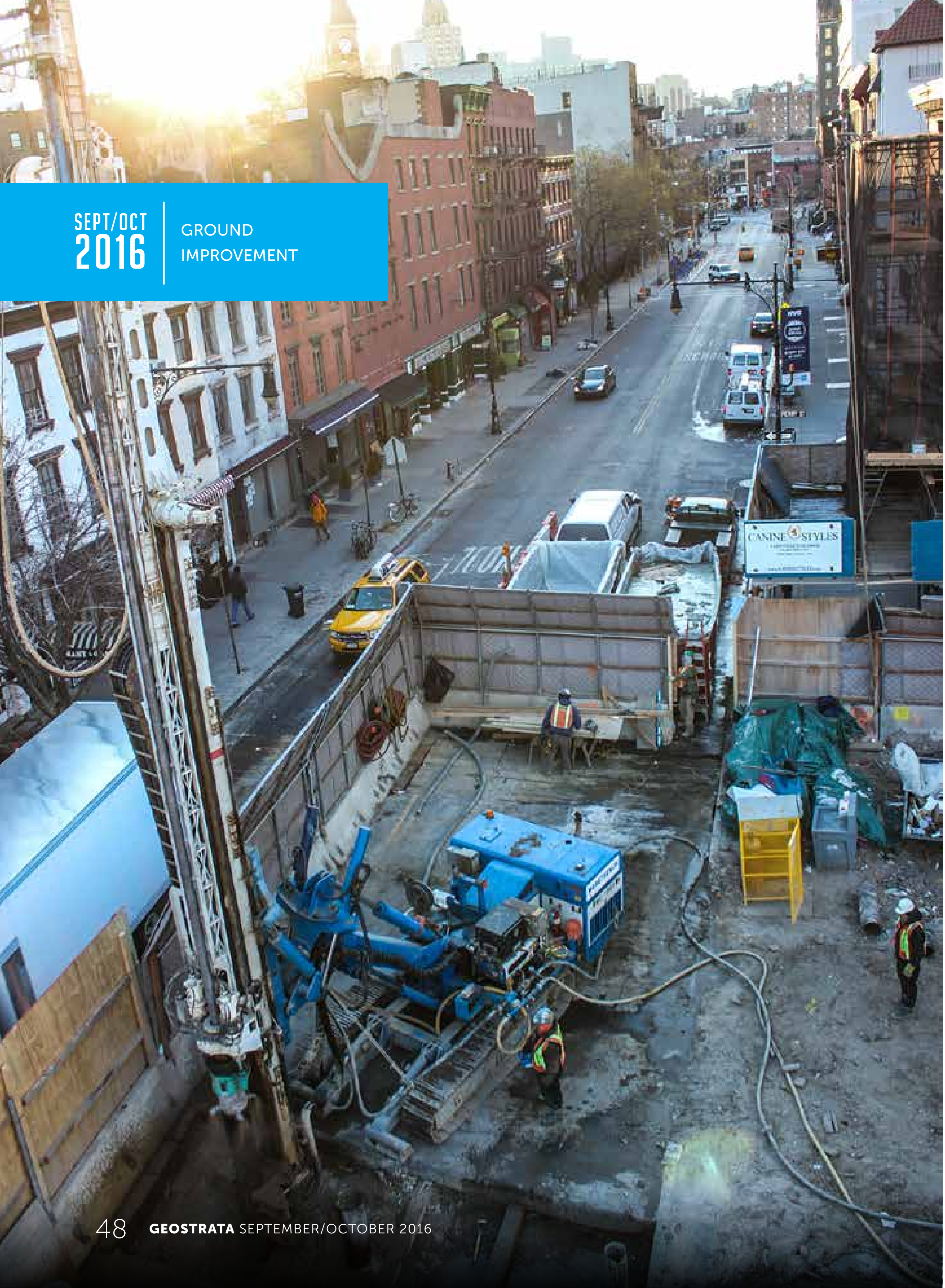
Figure 1. Jet grouting in urban areas is often performed immediately alongside pre-existing structures, and here it is taking place alongside an active subway line that runs beneath this street in lower Manhattan. Jet grouting is best performed with a mast extension so that the columns can be pulled in one smooth, continuous motion. (Photo courtesy of Moretrench.)



GROUND IMPROVEMENT FOR UNDERGROUND CONSTRUCTION

The Good, the Bad, and the Ugly

By Paul C. Schmall, PhD, PE, D.GE, F.ASCE

Underground construction is "special" because the work may be performed at great depths and under high groundwater pressures. All too often, it seems to take place in urban areas where there is limited surface access, but a seemingly unlimited number of infrastructure features and structures. Murphy's Law of Geotechnical Engineering tells us that most of those structures will be very sensitive, and built on shallow foundations that are vulnerable to the adverse effects of construction. It's in these locations that engineers and contractors find themselves learning the hard lessons of working underground: the ground will relax with deep excavation, and ground loss or instability will occur due to the presence of groundwater. There are many good situations where ground improvement will be well suited to address a concern, some bad situations where ground conditions may be unexpected or ground improvement may be insufficient, and downright ugly events when the bad isn't recognized and blow-ins and catastrophic ground loss occurs.

Stiffening the Ground

The physical constraints associated with urban construction often prevent installation of relatively robust excavation support systems (e.g., secant piles and slurry walls). In those cases, ground improvement may stiffen the ground, which will, in turn, minimize excavation-induced relaxation. Then less robust shoring systems can be implemented.

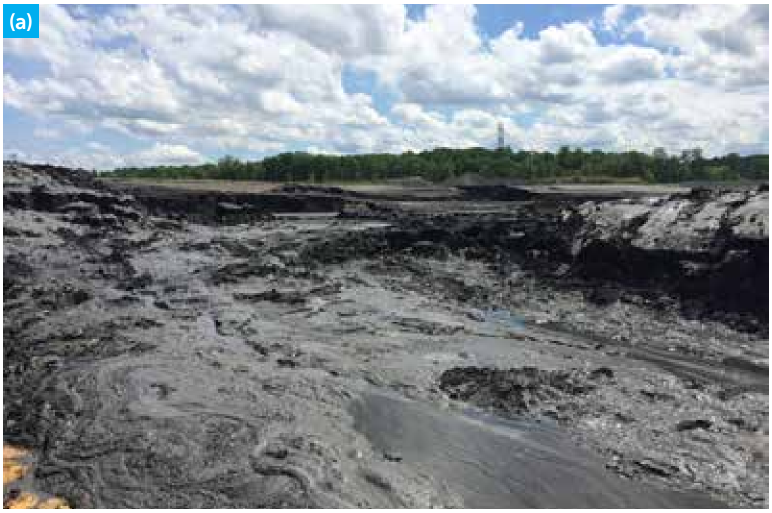
Permeation grouting is an option where the soils are coarse and clean enough to allow for the penetration of microfine cement or chemical grouts such as sodium silicate. Practitioners must manage grout loss through existing nooks and crannies when grouting alongside existing structures; targeted pre-grouting may be required.

Compaction grouting, or "low mobility" grouting methods, can quickly deliver appreciable grout volumes to stabilize a structure when unanticipated movement occurs during excavation, as opposed to permeation grouting, which is typically performed prior to excavation. Compaction grouting has been successfully performed in Manhattan alongside 100^{+}-year–old, multi-story brick buildings where the drilling of new, deep foundations or utility work adjacent to the structure has resulted in building movement. However, a liability of the method is that it can exert significant concentrated forces to existing structures.

Compensation grouting involves the finesse of widespread, more evenly distributed, low-volume, pin-pointed, repeated fracture grouting injections through sleeve-port pipes performed concurrently with an excavation or immediately upon movement of a structure. This method is typically used to protect a sensitive structure when there is no direct access to the structure itself. In practice, there is uncertainty associated with controlling the movement of a structure that cannot be touched. The characteristics of the ground, the weight of the structure, and the rheology of the grout are just a few of the variables that determine the efficiency and effectiveness of the grouting. All compensation grouting is thus done observationally. Where there is direct access to a structure, a proactive, positive geo-structural method of controlling movement, such as micropiles, may be more desirable.

Jet grouting is a very versatile ground improvement tool that is applicable over a wide range of soils (Figure 1). Jet grout underpinning of a structure may be considered a positive structural support alternative if the foundation is accessible. A number of aspects of jet grout underpinning are advantageous, including the ability to put it in place without below-grade excavation work. This is particularly beneficial when the underpinning must be extended below the water table. In the context of deep excavations, jet grouting may be used as the primary means of groundwater control and support of excavation, but is more commonly used to close gaps in perimeter cut-off walls where utilities cannot be relocated. Or, it might be used to create a manmade bottom seal for a watertight excavation. Jet grouted closures are also common where dissimilar types of cut-off walls meet.

Figure 2. (a) Saturated fly ash exhibits a uniquely difficult instability that is a purely non-cohesive material with almost spherical particles. The ash is sluiced into holding ponds so it is loose, wet, and runny. (b) Dewatered fly ash will exhibit apparent cohesion and can be cut vertically or nearly vertical. (Photo courtesy of Moretrench.)



Controlling Groundwater

Ground improvement is a different animal altogether when it's relied upon to control groundwater. The phrase "groundwater control," first of all, is very nondescript. It can mean "to modify the undesirable behavior of saturated ground." From a contractor's perspective, it is the difference between "wet" and "dry" ground (the dry condition being ground minus "free" water). An extreme example of this point is the case of fly ash. New federal regulations currently mandate the draining and closure of all the nation's power producers' fly ash ponds, which has made this a very hot topic. Fly ash, which typically consists of about 80 percent silt size and spherical particles, has historically been a problematic, uncontrollably runny, and easily neglected waste product (Figure 2a). It's usually handled by primitive rim-ditching and sumping methods, although pre-drainage dewatering with wells and wellpoints works amazingly well. Regardless of the dewatering method selected, the transformation is astounding: the runny material, when drained, can be cut vertically or near vertically (Figure 2b). When the "free" water is drained from the ash, it transitions from a soup to a very nice, soil-like material with apparent cohesion and "stand-up time." The transition occurs where the pore water pressure goes from positive to negative, and the water acts more like a glue than a lubricant. To illustrate these positive effects, think of a sand castle at the beach, which is built with moist sand rather than dry sand. In the same way, a 50,000-lb excavator can track out onto a drained fly ash pond without sinking.

A real-life example of apparent cohesion with drainage of fine-grained soil can be seen in the rebuilding of lower Manhattan over the last 15 years. The rapidly dilatant silt, locally known as "bull's liver," is a soil similar to fly ash in grain size distribution and completely lacking plasticity. It must be drained to be workable at all. The World Trade Center "bathtub" excavation and the adjoining Dey Street Connector were two sites that were completely encompassed by cut-off walls, but still required pre-drainage dewatering to excavate and

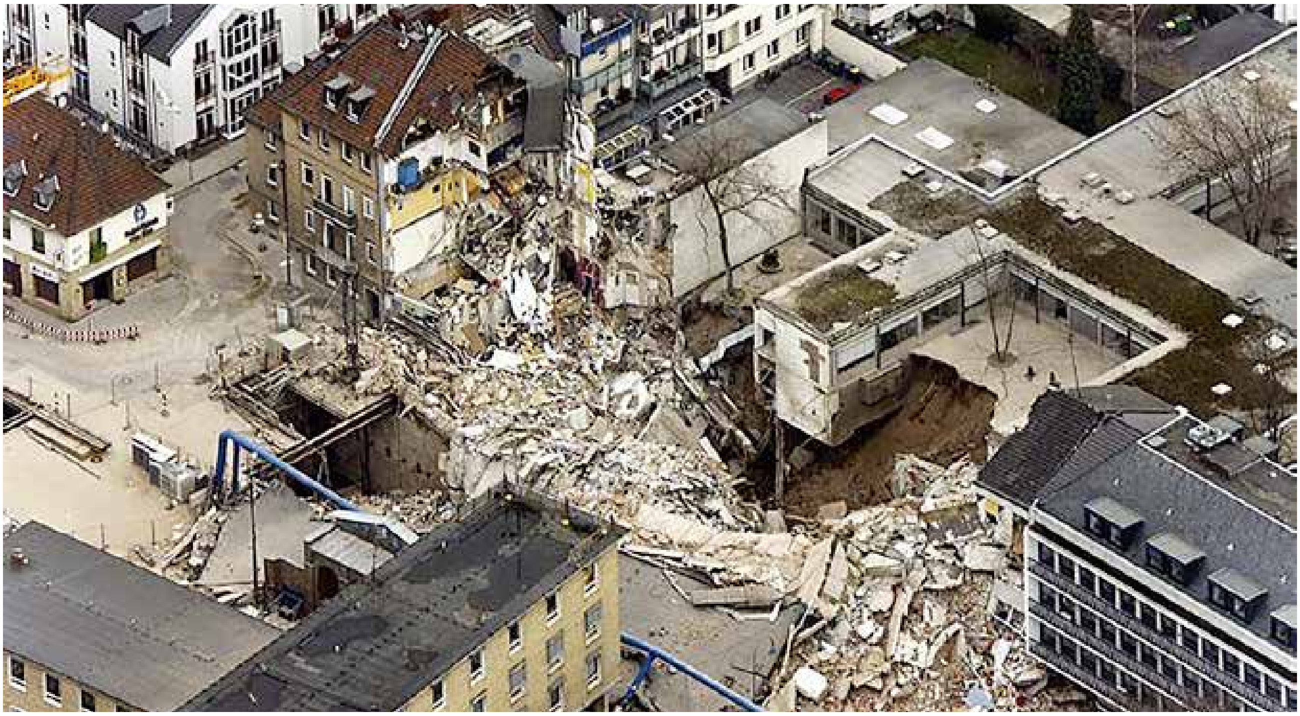


Figure 3. The scale of the 2009 collapse of a six-story archive building and two neighboring apartment buildings in Cologne, Germany, is evidence of the powerfully destructive effects of soil erosion with groundwater flow. (Photo courtesy of TunnelTalk.)

track equipment on the site. It should be noted that many contractors fall victim to thinking that pre-drainage dewatering is not necessary when the soils are of low permeability. The most difficult ground is a fine, non-cohesive silt like a Manhattan bull's liver.

Running Ground

A slightly more complex meaning of "groundwater control" is to prevent the erosion of soil due to flowing groundwater. Everyone who has dug a hole at the beach knows "running" ground. The different behaviors of wet ground have been best defined by those who suffer from it the most — the soft ground tunnelers. Renowned tunneling expert Ron Heuer, in his 1987 paper "Anticipated Behavior of Silty Sands in Tunneling," set the language for the different wet ground conditions based on his intense participation in the construction of deep tunnels, including the Washington Metro system in the 1970s. Thanks to Ron, tunnelers understand the distinction between firm, raveling, cohesive running, and running ground. Running ground, like digging a hole at the beach, is certainly a situation to be feared in underground construction. The relevant ground improvement technique may simply be pre-drainage *dewatering*: the installation of wells, wellpoints, or ejectors to remove the "free" water from the soil.

An example of the potential impacts of running ground would be the 2009 collapse of several buildings in Cologne, Germany (Figure 3). The cause of the horrific disaster, which claimed two lives, has been attributed to a lack of passive resistance at the toe of a slurry wall, which occurred when uncontrolled (unfiltered) open pumping from inside a deep shaft inadvertently resulted in erosion of ground due to flowing groundwater. In general, though, the risks associated with conventional dewatering are relatively low and do not end in catastrophic failures.

Groundwater Cutoff

The most complex and probably the most frequently assumed intent of "groundwater control" is to eliminate the flow of groundwater with a positive cut-off that also provides structural support of an excavation. This may be accomplished with conventional vertical cut-offs such as steel sheeting, slurry walls, secant piles, or with ground improvement such as jet grouting, soil mixing, and, to a lesser extent, permeation grouting.

Construction of groundwater barriers has been a topic of high priority in the wake of hurricanes Katrina and Sandy. Levees have been stressed to the point of failure. From those events, lessons have been learned that point to the need for increased groundwater barrier robustness.

The *deep mixing method* (DMM) has been used for groundwater barrier construction, but more appropriately for improved embankment support and bearing capacity. DMM's distant relative, cutter soil mixing (CSM), which is more of a ground displacement method, has enjoyed sole success among other ground improvement methods in the coralline limestone of Miami for water cut-off as well as excavation support. For years, geotechnical contractors had attempted to improve the weak rock there with grouting methods, achieving limited success. Up until several years ago, below-grade parking in Miami was nonexistent — and for good reason.

As this article is being written, a frozen barrier with an enormous 5,000-ft-long perimeter and a depth of

Figure 4. **Very permeable karst rock in Columbus, OH, was grouted for deep shafts and connector tunnels. Sizable grout-filled karst features are visible in the heading. (Photo courtesy of Moretrench.)**

100 ft is being activated around the failed nuclear reactors at Fukushima, Japan. The barrier is being used to create a perfectly continuous cutoff through myriad underground subsurface obstructions, with only small volumes of spoils generated. Closing the barrier may be challenging due to size, the complex ground and thermal conditions, and the up-gradient groundwater build-up that will occur as the frozen wall gradually closes. An incredible amount of engineering will likely be needed to resolve those challenges.

Groundwater recharge should be considered where excessive drawdown is an issue and where a cut-off would traditionally be used. Before the connection between groundwater treatment and efficient recharging was understood, the process had been avoided because it required significant maintenance. In close proximity to a national historic structure, groundwater leakage into the excavation of a new, deep building under construction resulted in lowering of the groundwater beneath the structure, which was built with a thick mat foundation sitting on compressible soils. When the groundwater lowering was recognized in site piezometers, recharge wells were installed between the excavation and the structure, and water levels were rapidly returned to normal. Treated water was used, and the system never required maintenance.

The "Bathtub" Excavation

When it's problematic to lower the groundwater table, very often the groundwater control approach is the "bathtub" excavation: perimeter vertical cut-off walls and a naturally occurring or man-made impermeable bottom. In some cases, the cost is warranted, but in many cases it is based upon unfounded fears or perceptions. The perimeter vertical cut-off is typically more conventional geo-structural work. Extending the vertical walls down to a naturally occurring bathtub bottom is the best approach, provided a natural bottom exists and the limits of applicability of vertical cut-off methods to reach it are not stretched.

Where no naturally occurring, low-permeability cut-off stratum exists below subgrade, a bottom plug can be constructed, either shallow (at-subgrade) or deep (a blanket well below subgrade). There are advantages and risks associated with each approach. The shallow, at-subgrade bottom seal must be perfect. A deeper blanket can accommodate some leakage, but the depth of the seal demands significant quality control rigor. A manmade bottom seal will typically be constructed with jet or permeation grout. A jet grout bottom seal for a deep excavation is one of the riskiest things that a geotechnical contractor can do because of the complexities of the work and no tolerance for error.

When rock is the impermeable bottom for a bathtub excavation, sometimes it must be improved as well. All of the East Side Access and 63rd Street Connection bathtub excavations in New York City required grouting of the top 10-15 ft of rock beneath the perimeter slurry walls. It is somewhat counterintuitive, but grouting of rock is most effective when the rock is wide open. The recent OARS tunneling project to control combined sewer overflows in Columbus, OH, required slurry grouting in very permeable karst rock for 180-ft-deep tunnel access shafts (Figure 4). The end result was essentially dry shafts. Grouting rock with infilled fractures and fissures can be an

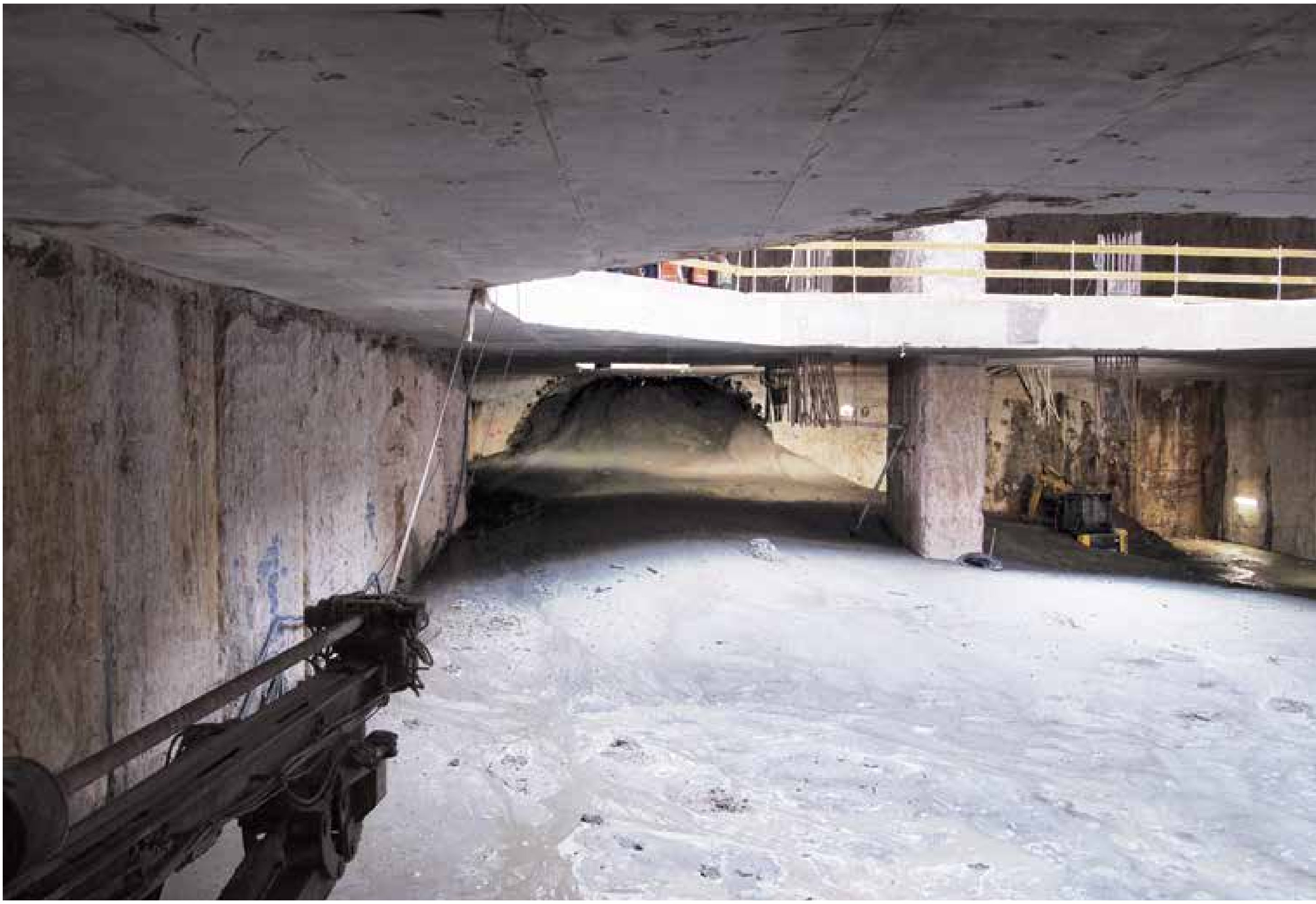


Figure 5. Post-failure conditions following collapse of jet-grouted soil canopy during construction of a tunnel at the Powisle Metro Station in Warsaw, Poland. An imperfection in the jet-grouted canopy caused significant ground loss. Note the buried equipment in the right side of the photo. (Photo courtesy of Metro Polska.)

issue, particularly if the rock will be exposed in the excavation and water flow may flush the rock clean. Jet grouting has been used successfully (and as a last resort) in rock to replace sand infilling in widely open features.

When Things Get Ugly

Where the bathtub approach is adopted, it must be executed flawlessly or significant and sometimes catastrophic blow-ins may occur. The recipe for a blow-in is high groundwater pressure + potentially unstable soils + a small defect in a cut-off. Usually, there is no conclusive way to control the situation or pinpoint the leak. The effectiveness of the bathtub system as a whole is difficult to verify. Field verification prior to excavation is very important, but often highly uncertain. If there are windows, they are quite difficult to find.

The big concern is the potential for erosion of soil with flowing groundwater. When the excavations extend well below the water table and the groundwater pressures are high, a fist-sized defect may reveal itself with a vengeance. This is when things get ugly. The vast majority of catastrophic ground failures with deep excavations can be traced back to one of three things: 1) a design flaw in the support of excavation (usually in developing countries, where standards of practice are less rigorous), 2) a quality control issue in the construction of the support of excavation/groundwater cut-off, or 3) where unanticipated ground conditions resulted in groundwater inflow. The first two situations are manageable, but it's an unfortunate reality that ground uncertainty will always accompany underground construction.

Ground freezing may be warranted when uncertainties in ground conditions could result in groundwater control failure or when confidence runs low about a particular cut-off technique. It is often considered the last resort because it is typically not the cheapest, but it is the most assured. A tunnel access shaft in Buenos Aries was frozen after 14 months of failed ground improvement attempts, including dewatering, permeation grouting, and jet grouting.

Another example of problems encountered during construction is the Powisle Station on the Warsaw (Poland) Metro project. A differing ground condition and an imperfection in a jet-grouted canopy over a NATM tunnel resulted in a rapid inflow of almost 300,000 ft^3 of non-cohesive silts (Figure 5). An immense nitrogen freeze had to be performed to make up time. In fact, catastrophic failures usually end up being frozen because the process is very effective in disturbed ground.

Complex and difficult ground conditions lend themselves to ground freezing as well. For example, freezing was considered the only viable option for sequential excavation mining (SEM) of the East Side Access project's Northern Boulevard Crossing in New York City (see the May/June 2014 issue of *GEOSTRATA*, pp. 28-32). Here, complications included difficult ground, high groundwater with limited drawdown permitted, a moratorium on surface access, and an active subway box immediately above the proposed tunnel crown. Carefully controlled horizontal ground freezing extending to bedrock created a canopy above the tunnel crown to provide a stable, watertight excavation for problem-free mining (Figure 6).

It's All About the Right Match

Underground construction will often rely upon ground improvement for stiffening the ground and providing groundwater control. Some techniques can do both and under a wide range of conditions. Matching the appropriate technique to the actual conditions is very important for stiffening the ground, but absolutely imperative when providing groundwater control in certain soils. Experience has shown us that ugly situations with deep excavations are almost always traced back to groundwater — the bad actor in underground construction. The lubricating effects of groundwater and the potential to erode soil with groundwater pressure will expose any bad situation and make it ugly. Understanding when there is potential for a bad situation, selecting the right technique, and implementing it well makes all the difference. GS

PAUL C. SCHMALL, PhD, PE, D.GE, F.ASCE, is vice president and chief engineer at Moretrench in Rockaway, NJ, where he has worked with grouting, ground freezing, and dewatering for 29 years. He is also a past recipient of the Wallace Hayward Baker Award for innovation in ground improvement. He can be reached at *pschmall@moretrench.com*.

Figure 6. The newly completed Northern Boulevard tunnel in New York City lies beneath an arch of frozen ground. Ice over the horizontal freeze pipes can be seen around the outside of the tunnel. (Photo courtesy of Moretrench.)