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Pre-conditioning/Pre-excavation Grouting of the Soils Prior to Tunnelling Below Highways & Railways: Case Histories from the Past Decade

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ABSTRACT

Pre-excavation grouting is a predictable and reliable technique performed to prevent or minimize settlement in advance of, or during the tunnelling operation. It safeguards the infrastructure above the tunnel alignment. Cement based suspension grouts and sodium silicate based grouts are frequently injected to consolidate and strengthen the formation and create a reinforced canopy above the tunnel trajectory. Grouting is typically performed through permeation and permeation in conjunction with hydrofracturing. Multiple injection passes through steel sleeve pipes are ideal, since they create an effective forespiling system to facilitate tunnelling without causing unacceptable settlement, even with minimal overburden thickness. Ten pre-excavation grouting projects performed in the North America are discussed in this paper.

GENERAL APPROACHES FOR PRE-EXCAVATION GROUTING PRIOR TO TUNNELLING

In order to protect structures and minimize or prevent settlement, grouting the soils prior to tunnelling has been a classic and proven concept for more than 5 decades.

The following pro-active grouting techniques and systems are typically used:

- Permeation grouting single pass
- Permeation grouting multiple passes and more than 1 type of grout
- Hydrofracture grouting
- Permeation grouting in conjunction with hydrofracturing
- Jet-grouting

A commonly used reactive grouting system to attempt and achieve the same, is compensation grouting. The latter can be used in conjunction with some of the pro-active techniques, for soils that cannot be adequately treated prior to tunnelling.

Permeation grouting and permeation grouting in conjunction with hydrofracturing -provided the soils have a hydraulic conductivity (permeability value) greater than 0.0005 cm/s - remain the least intrusive, clean, predictable grouting systems to treat the soils prior to tunnelling. In order to be successful it is absolutely necessary to use sleeve pipes and to perform multiple grout passes, via the same sleeve pipes with reasonably durable grouts.

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Sleeve pipes can be installed vertically or (preferably and where possible) horizontally to create an arch of grouted soil covering at least the upper half of the future tunnel. The advantage of horizontal sleeve pipes (whether steel or plastic) is, that they can be transformed into a grouted forespiling system, a continuous, reinforced grouted earth, whereby only a short span at the time is unsupported during tunnelling.

The grouts selected for permeation grouting must be suitable for the encountered soils.
In general, properly formulated, stable cement based suspension grouts are only suitable for the grouting of soils with a k-value (permeability value) in excess of 0.08 cm/s. Stable, microfine cement based grouts are typically suitable to permeate soils with a k-value greater than 0.001 cm/s, provided the silt content is less than 12%. Both these 2 types of grouts however can be used for “permeation grouting in conjunction with hydrofracturing” when the soils have a k-value which is one order lower.

Solution grouts can typically be used for permeation grouting as long as k is greater than 0.0005 cm/s. The layer thickness and the silt percentage also play an important role in the injectability of the soils and the permeability limits are therefore only indicative.

It is a proven concept to perform grouting in several grout passes, alternating between solution grout (typically sodium silicate based grout) and cement based grout, to create grout cylinders with a predictable diameter and mechanical characteristics.

Because of the high pH of the cement based grout, sodium silicate based solution grouts tend to be considerably more durable than if only sodium silicate based grouts are used.

During the first grouting pass, grout will predominantly permeate the most pervious layers in the pressurized grout zones. Once the first grouting pass is finished, solution grout will sag, under gravity. It should be noted that all solution grouts are exothermic reactions. The soil dissipates the heat and hence it will take considerably longer for the grout to cure than what the pot-life indicates. As a result there is grout migration after the grouting pass is finished, in pervious soils. During the second grout pass, the layers that were originally the most pervious are now the least pervious, hence grout will permeate more readily into these layers during the second grout pass.

By alternating solution grouts with suspension grouts, the suspension grouts will hydrofracture through the untreated or partly treated soil layers. From the grout “wings” grout will permeate a nominal distance into the soil on both sides of the induced fractures.

By executing 3-4 grout passes, the formation gets treated more uniformly and grout cylinders with a predictable size are formed. The grout spread that can be obtained with the equation of Cambefort-Naudts

$$r_{spread} = \sqrt{\frac{2k\upsilon P_{eff} t_{set}}{\upsilon_i \delta_i \ln\frac{R}{r_o} n_i} + r_o^{\,2}}$$

Where:

k = hydraulic conductivity horizon for the injection product in cm/s

υ = kinematic viscosity of water

P_{eff} = effective injection pressure in cm water column

t_{set} = pump time of the grout in seconds

υ_i = kinematic viscosity of the grout

δ_i = specific gravity of the grout

R = distance from the middle of the sleeve pipe to where the influence of the grouting pressure is not being felt in centimeters

r_o = radius of the borehole in centimeters

η_i = accessible porosity by the grout

One of the most infamous pre-excavation grouting programs in history took place during the mid-seventies in Nurnberg (Germany). A permeation grouting program, whereby sodium silicate, injected via sleeve pipes failed to prevent settlement of buildings during the tunnelling operation. The sodium silicate had been neutralized with ethylacetate, which, similar to the diabese esters and inorganic acids only results in a temporary soil modification. Because of delays with the tunnelling operation, the reaction had been reversed and the benefits of the soil grouting were gone at the time of tunnelling, causing catastrophic settlements and lead to the bankruptcy of the leading German contractor.

Especially when grouting below the ground-water table, classic sodium silicate based grouts are quickly disappearing, even when neutralized more than 60%. If a higher degree of neutralization is used, the set time of these evolutive solution grouts are too short to obtain adequate permeation. For the longest time, the alternative to the “unstable” sodium silicate based grouts were water-reactive polyurethane grouts and acrylamide grouts. The latter are non-evolutive solution grouts and have a viscosity equal to water. Some formidable soil grouting projects have been performed with both polyurethane and acrylamide grouts.

There are however permanent, inexpensive, non-evolutive sodium silicate grouts, even when injected below the water table but they are not widely used, since the main grouting contractors are not familiar with them. Very few grouting practitioners appear to be knowledgeable on how to determine/calculate the degree of neutralization. Hence sodium silicate based grouts have a dismal record in North America for application in water saturated soils. In relatively dry soils, proper neutralization of the sodium silicate is less critical, which explains the success enjoyed by the unsophisticated grouting contractors.

Jet grouting has been used for the treatment of a large variety of soils. Whilst it is technically feasible to use jet-grouting in soils that can be treated with permeation grouting, preferably, it should only be used in soils with low hydraulic conductivity. Because of its perceived simplicity and in spite of the mess (spoils) that is created, it appears to be the technique of choice for some grouting contractors. Heaving and settlement of the structures to be protected has been a problem. Executing a horizontal jet grout curtain remains a major challenge with this technique.

CASE HISTORIES

The following case histories illustrate that a proper approach to pre-excavation grouting invariably lead to a successful outcome, in spite of the many challenges.

1. Chaska West Interceptor, 2005

Project specifics. A 1.9 meter (76 inch) diameter tunnel bore had to be constructed below US 41 Highway as part of the West Interceptors infrastructure being constructed in Chaska, Minnesota. The tunnel trajectory was scheduled to be constructed approximately 4.2 meters (14 feet) below an important road artery, through a fine grained sand formation for a distance of 60 meters (200 feet). In order to protect the road artery and a 0.3 meter (12 inch) diameter clay sanitary sewer located 2 meters (6.5 feet) above the tunnel crown, a soil grouting program was designed and implemented prior to the tunnel construction to consolidate the soils above the planned tunnel trajectory.

The grouting program. The grouting program consisted of installing 2 horizontal steel sleeve pipes 0.6 meters (2 feet) above the tunnel crown. Each sleeve pipe was off set 0.9 meters (3 feet) off center line of the tunnel alignment and installed using directional drilling techniques.

A multiple injection pass grouting program was performed to inject regular cement based suspension grout and sodium silicate based grout to consolidate the fine grained sand formation. Since the in-situ k-value of the soil formation to be treated was lower than 10^{-2} cm/s, the soils were predominantly injected through hydrofracturing in conjunction with permeation grouting techniques. Not only did the low permeability of the formation made it difficult to treat, but an existing leaking clay sanitary sewer line, located less than 1.5 meters above the sleeve pipe, provided a number of preferential flow paths for the grout to travel. After injecting a total of 12757.5 liters (3375 gallons) of grout via the sleeve pipes and based on the presence of the leaking sewer pipe above the tunnel, a compensation grouting program was contemplated as an additional safety measure during the pipe jacking activities to further ensure that no settlement to the infrastructures above would take place. During the pipe jacking operations and after "fracturing" the sleeves, each sleeve pipe was pressurized to 100 psi with a very slow curing grout. The intent of this operation was that if any soil disturbance occurred around the sleeve pipes, the soil disturbance would be detected by a sudden grout take at which time the tunnelling operation would have been halted, while compensation grouting operations would reverse the disturbance.

Effect of treatment. Due to the successful pre-excavation grouting program executed prior to tunnelling and due to the diligence of the tunnelling crew, no soil disturbance was created. The compensation grouting program therefore did not have to be fully implemented. The tunnel was mined in less than 48 hours, without causing any settlement to the overlying structures.

2. CP & BNSF Railway Crossings, Newport, Minnesota

Project specifics. A 1.4 meter (4.5 feet) diameter tunnel, approximately 200 feet long, had to be mined approximately 1.5 meters (5 feet) below 3 railway tracks and 0.6 meter (2 feet) below sensitive fiber optic cables without causing settlement to the infrastructure. Figure 1 provides a plan view of the site and the infrastructures that required protection during the tunnelling operation. Based on the geotechnical information available, the tunnel was expected to be mined through a weak sandstone formation, however when the jacking pit was excavated, a fine sandy soil formation was uncovered at the planned tunnel elevation. Additional geotechnical investigations was performed along the tunnel alignment which confirmed that the sandstone layer was actually deeper than anticipated. This unexpected situation posed great concern to all parties involved, especially since the tunnel could not be constructed at greater depth.

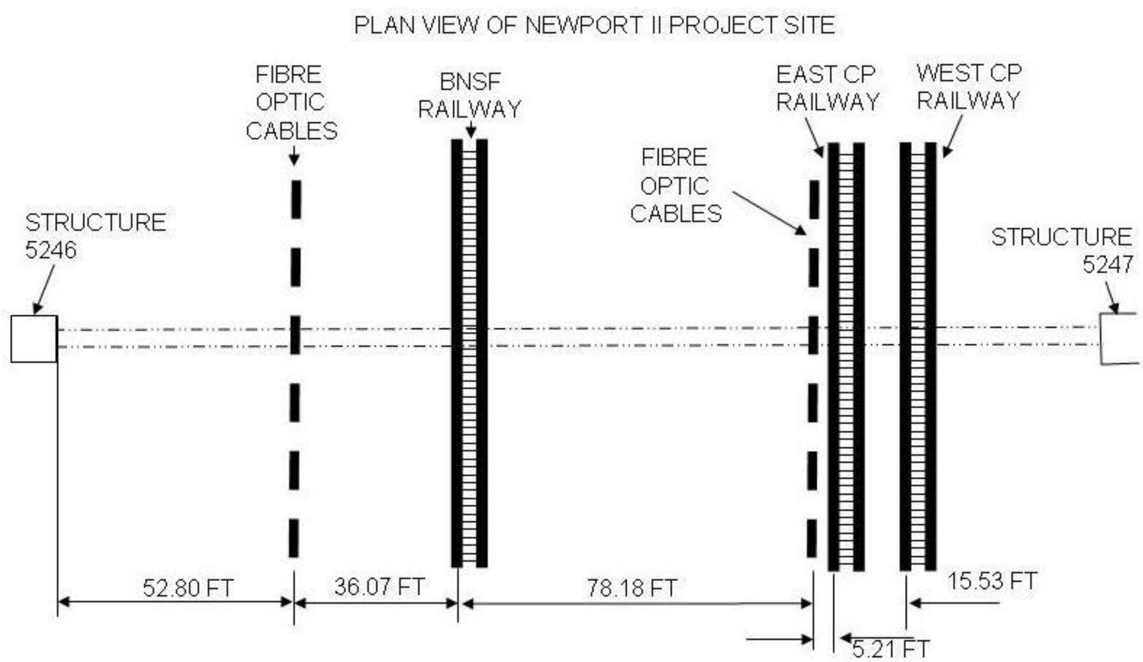

Figure 1: Plan view of the site

The grouting program. To ensure the integrity of the infrastructure during tunnelling, a grouting program was implemented prior to tunnelling. Due to the restrictions imposed by the railway companies, no sleeve pipes could be installed in the upper 3 feet of overburden below the railway tracks. Eight horizontal sleeve pipes were therefore installed around and outside of the perimeter of the planned tunnel trajectory to create a grouted soil conglomerate as depicted in Figure 2. Steel sleeve pipes were selected in lieu of plastic pipes in order to create a reinforced grouted soil conglomerate, acting as a forespiling system. Two injection passes of regular cement based suspension grout and two injection passes of sodium silicate based grout was performed in each sleeve pipe in order to allow the least pervious soil layers to be treated following the injection of the most pervious layers in previous passes. To ensure that the grouting pressures would not raise the railway tracks, monitoring points on the tracks were surveyed frequently and the grouting operation was monitored in real-time using the CAGES NS system, which allowed to detect hydrofracturing events. Once the theoretical grout volume was injected in all sleeve pipes and we had a record that the adequate grout spread was achieved, the grouting operation was concluded.

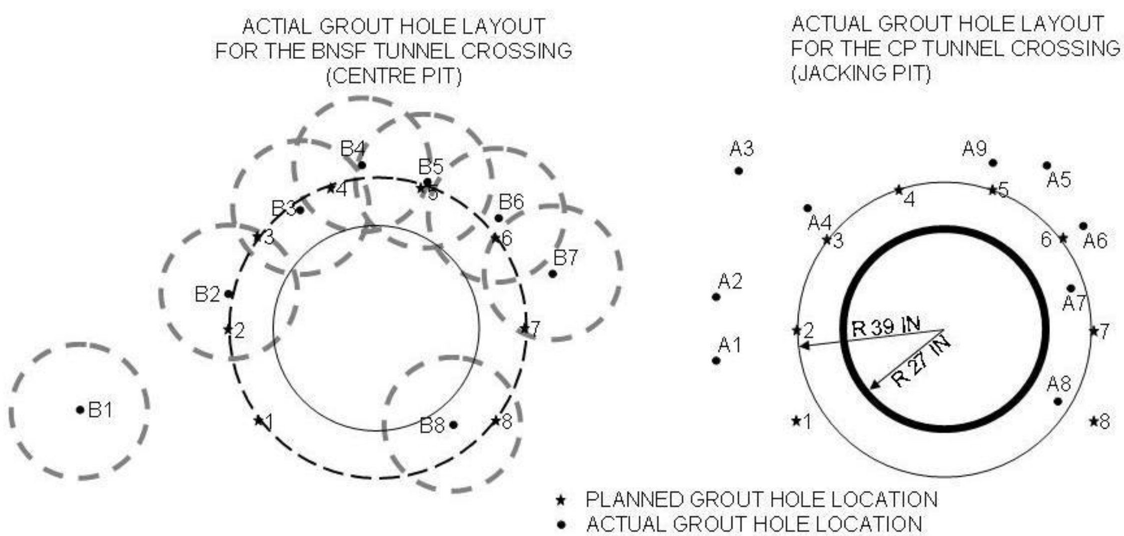

Figure 2: Grout hole layout for the BNSF and CP railway crossing

The challenges. The sleeve pipe installation turned out to be very challenging. The sleeve pipes above the crown of the tunnel had to be installed below fibre optic cables, which were located approximately 0.6 meter (2 feet) above the tunnel. Since steel sleeve pipes were used, these sleeve pipes could not be installed in the tunnel trajectory as it would hinder the advancement of the tunnel, therefore these sleeve pipes had to be installed in a 0.6 meter (2 feet) target zone. In addition to these restrictions, large boulders (i.e. 0.5-1 meter diameter in size) were encountered during the drilling and sleeve pipe installation, which caused the drilling head to deviate more than 1.5 meter (5 feet) off target. To make the sleeve pipe installation easier, the sleeve pipes had to be installed from a pit located between the BNSF and the CP railway. Cutting the drilling distance in half, facilitated the sleeve pipes to be installed within an acceptable deviation from the target locations.

The limited thickness of overburden posed its share of problems during the grouting operation. The lack of confinement caused the grout to easily migrate and break out to surface, which impeded on the grouting progress. Photograph 1 illustrates the sleeve pipes installed in the CP railway embankment and several grout leaks (breakout to surface) which occurred during grouting due to the lack of overburden confinement.

Photograph 1: Sleeve pipes installed through the CP railway embankment around the planned tunnel trajectory

The grouting operation was executed in nine injection passes. This allowed the grout to cure in the upper soil layers and systematically create confinement for subsequent injection passes. As the grouting operation progressed, fewer grout leaks to surface were observed, and eventually all sleeves were brought to refusal.

Effect of treatment. The grouting program resulted in the construction of overlapping grouted soil cylinders forming a continuous arch above the future tunnel trajectory. Typically, these grouted soil cylinders measured 1 meter (3 feet) in diameter, as observed and measured from within the tunnel during the tunnelling operation. The reinforced grouted soil arch around the tunnel allowed the tunnel to be mined safely without having any impact on the railway tracks and underlying utilities. An identical grouting program was implemented under the same railway tracks and utilities a short distance (3 km) away from this location and the same successful outcome was achieved: no settlement was recorded.

3. BWARI – US 23 Crossing, Columbus, Ohio

Project specifics. A 6,310 meter (20,820 feet) long precast concrete segment tunnel was constructed using an earth pressure balance tunnel boring machine, as part of the Big Walnut Augmentation Rickenbacker Interceptor. The construction of this 4.8 meter (16 feet) outside diameter tunnel was designed to cross highway US 23 a relatively short distance from the TBM launch area. Since the cover above the tunnel was relatively thin under this highway (i.e. approximately 7.5 meters (25 feet)), surface settlement was a concern.

A grouting program was specified to consolidate a large, rectangular block of soil above the tunnel trajectory to ensure that the settlement remained within the 12.5 cm (0.5 inch) tolerated settlement limit. The soil formation immediately above the tunnel trajectory contained approximately 10% fines and based on the sieve analysis and the in-situ permeability of this formation had a k-value of 4×10^{-3} cm/s based on Hazen's equation.

The grouting program. A multiple hole, multiple injection pass grouting program was designed and implemented above the tunnel trajectory. The grouting program consisted of injecting regular cement based suspension grout and sodium silicate based grouts utilizing permeation in conjunction with hydrofracturing grouting techniques through steel sleeve pipes installed above the tunnel trajectory. Two access shafts were constructed on either side of the highway to facilitate the installation of the horizontal sleeve pipes and to perform the grouting. Photograph 2 illustrates the grouting being performed from the West side access shaft. In lieu of grouting a large block of soil, a relatively thin reinforced grouted soil arch was proposed instead, in order to create a continuous, grouted soil arch. Four 4 sleeve pipes were installed approximately 5 feet above the tunnel trajectory (equally spaced 5 feet apart) to perform the pre-excavation grouting. An additional 2 sleeve pipes (installed approximately 2 meters (7 feet) above the first row of sleeve pipe) were installed as depicted in Figure 3. The second row of holes was installed as a precautionary measure in the event that compensation grouting would be required. The compensation grouting program would have involved injecting a cement based suspension grout above the tunnel trajectory during tunnelling operations. Any soils loosened by the tunnelling activities would have been replaced with cement based suspension grout, therefore reversing any soil disturbance. A total of 3 injection passes were performed through each of the four each sleeve pipes. The first pass consisted of injecting a regular cement based suspension grout, while subsequent passes were performed with a sodium silicate based grout. The CAGES NS grouting system was utilize to monitor, assess and evaluate the grouting operation in real time, which made it possible to inject on all 4 grout holes simultaneously.

Photograph 2: Grout injection being performed from within the West side access shaft

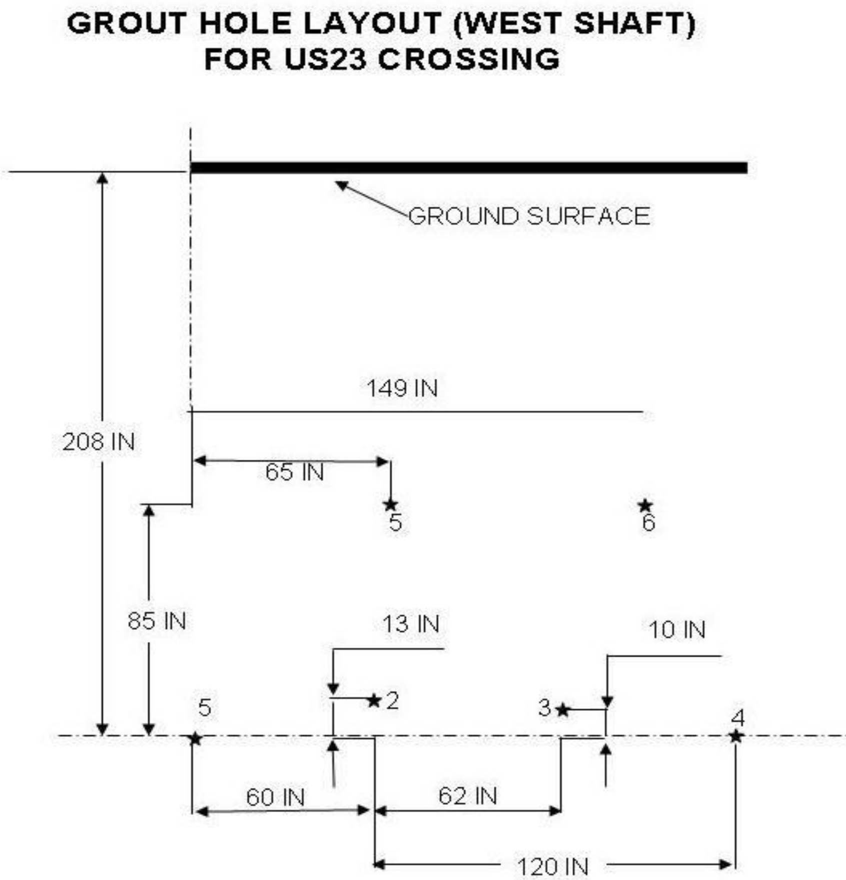

Figure 3: Sleeve pipe location above the tunnel trajectory

Effect of treatment. Due to the effectiveness of the grouting performed in the first row of holes, the compensation grouting program was deemed not to be necessary. This decision was based upon evaluating the data from the real time monitoring & assessment system (CAGES). The daily monitoring efforts of the survey crew provided no evidence of settlement or movement of the road surface during and following the grouting program. The tunnel was mined without causing any settlement whatsoever to the highway.

4. MAC Trunk Storm Sewer, Minneapolis, Minnesota

Project specifics. Two 4.2 meter (14 foot) diameter tunnels were constructed beneath a state highway near the airport in Minnesota. Both tunnels were constructed parallel to each other. The distance between the two new tunnels was 3 meter (10 feet) and they were located adjacent to an existing 28.8 cm (72-inch) diameter storm sewer line. The tunnels were mined approximately 19.3 meter (64 feet) below the road surface through fine silty sand, which was not readily injectable with solution nor suspension grouts. The length of the tunnels was 140 meter (463 feet).

Grouting program. In order to minimize settlement to the highway, a compensation grouting program was specified and implemented. It involved the installation of 5 horizontal steel sleeve pipes located 7.5 meter (25 feet) above the two tunnel crowns. Each sleeve pipe was equally spaced approximately 3.6 meter (12 feet) from each other as depicted in Figure 4. A series of extensometers were installed at strategic locations in order to monitor the movement of the soil located above the tunnel trajectory in real-time. A grout plant capable of producing 25 cubic yards of suspension grout per hour was mobilized on site to produce the required grout in a timely basis with reference to Photograph 3. A unique grout comprising of inexpensive ingredients was used to create a non-cement based suspension grout, specifically developed for this project. This very slow curing grout allowed the grouting crew to maintain each sleeve pipe under pressure during the tunnelling activities, without being concerned about the grout hardening up in the delivery system. As disturbance and loss of soil (overcut) were created by the tunnelling operation, the apparent Lugeon value (permeability value) suddenly increased and grouting was performed until the disturbance was reversed. The evolution of the apparent Lugeon value was monitored in real-time with CAGES. Grouting typically took place via double packers in 3 or 4 sleeve pipes at the time. This grouting technique allowed the two tunnels to be mined, while minimizing settlement to the highway. A total settlement of the road of approximately 2.5 cm (1-inch) was reversed by mud jacking the highway at the end of the operation.

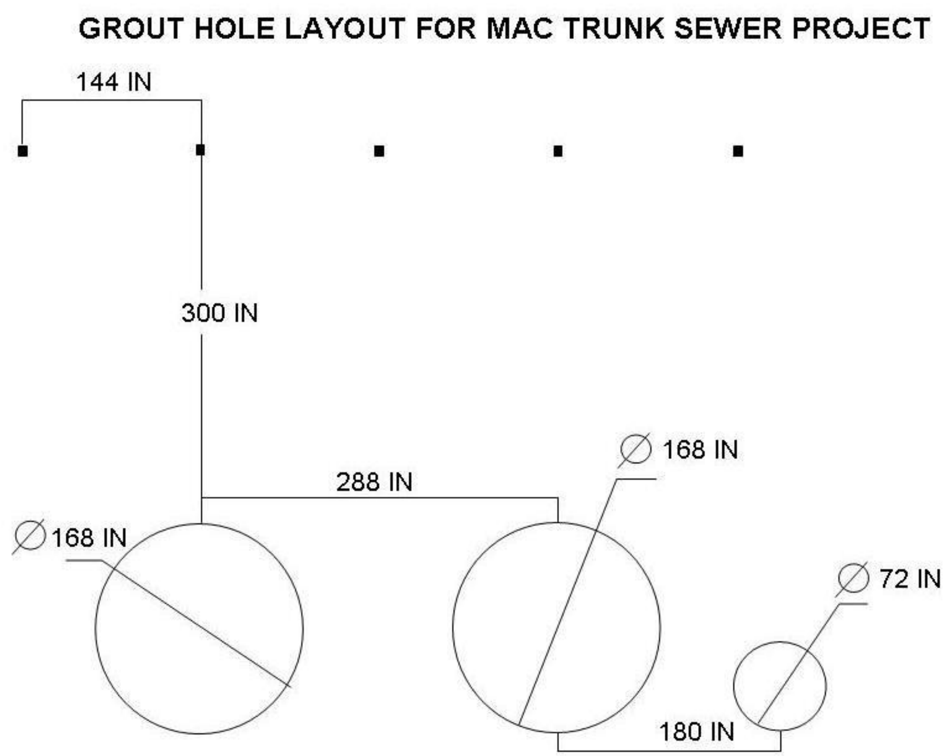

Figure 4: Sleeve pipe location for the MAC Trunk project

Photograph 3: General view of the batch plant and grouting lay-down area

5. Mineral Street Sewer Extension, Milwaukee, Wisconsin

Project specifics. A new 2.1 meter (84 inch) diameter sewer tunnel was constructed beneath an existing railway track embankment. Settlement of the active railway lines had to be minimized during the excavation of the tunnel in order not to interrupt CP Rail's operation.

The grouting program. An extensive grouted soil-conglomerate arch was created above the tunnel trajectory to prevent settlement of the CP Rail tracks during the excavation of the sewer tunnel through the underlying embankment. Photograph 4 depicts the grouting crew during the injection of sodium silicate grout via one of the sleeve pipes. The grouting program included the following:

- Installing horizontal steel sleeve-pipe
- Performing in-situ hydraulic conductivity tests over the entire length of the trajectory
- Depending on the in-situ permeability, injecting in multiple holes regular or microfine cement based suspension grouts, or sodium silicate solution grout (first pass)
- Re-injecting the recently grouted soil conglomerate with sodium silicate based solution grout (second and third pass)
- Real time monitoring with CAGES (Computer Assisted Grouting Evaluation System) to monitor the reduction in hydraulic conductivity as the operation was unfolding


Photograph 4: Grouting crew performing injection of sodium silicate based grout via the sleeve pipes

Settlement of the underlying embankment was perfectly controlled (no settlement whatsoever) and CP Rail's regular operations were not interrupted, when the tunnel was constructed.

6. Sarah Street Sewer Extension – CP Rail Crossing, Mishawaka, Indiana

Project specifics. During tunnelling activities of a 3.6 meter (12 feet) diameter sewer tunnel approximately 9 meters (30 feet) below 2 railway tracks through cobblestone and medium sand (no silt), significant ground loss was noted and an settlement of the railway tracks posed grave concerns to the Owner and Contractor. The mining operation was halted until a remedial and grouting program was tabled and approved. Although the tunnelling construction had a clever forespiling system in place, the use of open ended grout pipes, which did not allow re-access, was the downfall.

The grouting program. A grouting plan was develop and implemented which consisted of installing 9 horizontal steel sleeve pipes (40-60 feet long) fanning over the tunnel trajectory as depicted in Figure 5. The sleeve pipes were installed approximately 4.5 meters (15 feet) below grade. Photograph 5 illustrates the grouting crew during the sleeve pipe installation process. The grouting program was divided into 4 phases of work:

- Pregrouting downstream (south) of the TBM shield to reverse the disturbance caused
- Pregrouting of the soils upstream (north) of the TBM shield
- Performing compensation grouting during tunnelling

- Performing permeation grouting after the tunnelling operation below the tracks was completed to further consolidate the soil around the tunnel trajectory and ensure no settlement takes place at a later date

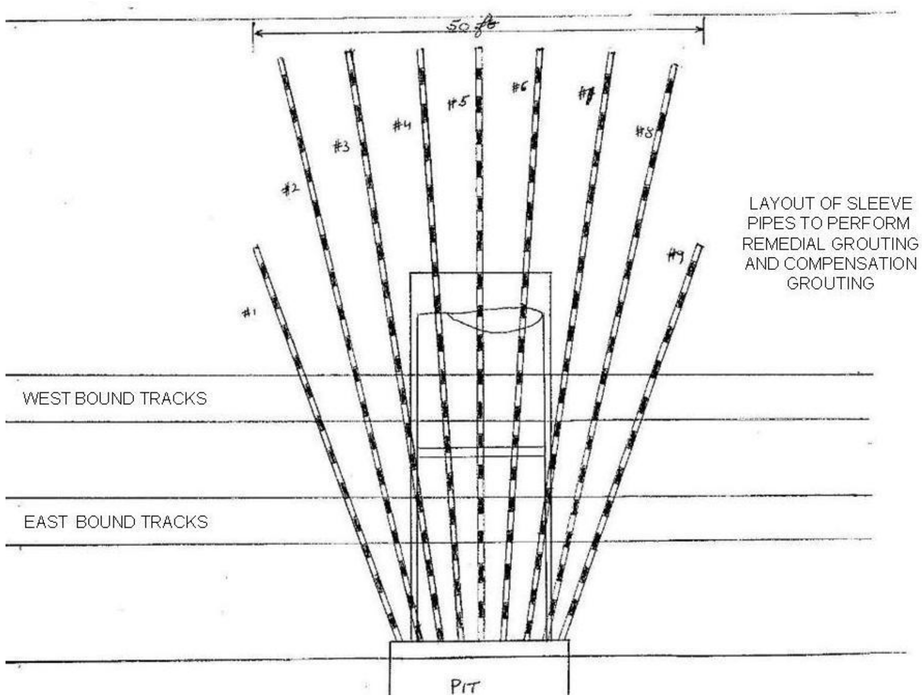

Figure 5: Schematic layout of the sleeve pipes fanning over the tunnel trajectory

Photograph 5: Grouting crew during the installation of one of the steel sleeve pipes

All sleeve pipes and several mechanical packers were built on site. A total of 25,890 gallons of regular and microfine cement based suspension grouts were injected. When the tunnelling operation resumed, no further settlement was recorded. The grout injected in the formation in conjunction with the forespiling system allowed for the safe construction of the tunnel below the railway tracks.

7. TTC Storm Sewer Relocation, Toronto, Ontario

Project specifics. A new 3 meter diameter sewer tunnel was to be installed beneath an existing subway tunnel (in operation). Unfortunately, the required trajectory of the sewer line resulted in a 40 meter long crossing. Settlement of the active subway line had to be minimized, arrested and reversed to prevent damage to the subway structure.

The grouting program. Based on the geotechnical information, the soils directly above the crown of the tunnel has a theoretical hydraulic conductivity slightly greater than 0.001 cm/s. When the access shafts were excavated, the soils which a permeation grouting program has been specified appeared to have a k value of less than 0.00001 cm/s. The grouting contractor proposed a compensation grouting program (the first one in Canada). The alternate compensation grouting program included the following:

- Jacking horizontal steel sleeve pipes from 4 access shafts to perform the grouting
- Installing inclinometer between the sleeve pipes and the subway tunnel to record in real time the movement of the soils
- Installing ground movement sensors to monitor movement of the existing subway tunnel
- Performing hydrofracture grouting of the soil (pre-conditioning of soils)
- Injecting slow curing, low-strength compensation grout during tunnelling
- Perform post tunnelling grouting to reverse any soil disturbances

Effect of treatment. Settlement of the founding subway soils was controlled and regular transit operations were not interrupted. The total settlement to the subway tunnel along the entire trajectory was less than 2 mm, a highly successful result since the overlying soils were saturated and silty in nature.

8. Fountain Street Crossing, Waterloo, Ontario (Canada)

Project specifics. An 85 metre long, 1.2 metre diameter, utility tunnel was constructed in Waterloo beneath Highway 401, the busiest highway in Ontario. The tunnel constructed approximately 5 meters below the pavement was mined through a geological outwash area containing predominantly boulders, with the space between the boulders filled by sand and silts (a so called “Karne”).

The grouting program. A pre-excavation grouting program was implemented to protect the highway from settlement during the tunnelling operations through a pro-active permeation grouting program. Horizontal sleeve pipes were installed along the alignment of the tunnel and used to form a grouted arch shaped soil mass surrounding the future tunnel. Various technologies were used:

- Directional drilling for accurate placement of the horizontal sleeve pipes. Major problems were encountered during drilling because of the presence of boulders. Drilling took place from both sides of the highway. More than 30 cubic meters of bentonite slurry were used to facilitate drilling.
- In situ hydraulic conductivity testing to determine the zones amenable for microfine cement based suspension grouts and the ones suitable for sodium silicate based grouts. Because of the extreme use of bentonite, the permeability of the soil had been substantially reduced. Sodium silicate based grout was therefore predominantly used.
- The use of sodium silicate to grout low permeability zones

Effect of treatment. As a result of a thorough geotechnical investigation, effective dewatering, a properly designed grouting program, and a well executed tunnelling operation, no settlement whatsoever was caused to the highway. A tunnelling attempt nearby (without grouting) resulted in the collapse of the highway. In spite of all the drilling difficulties, this project was a remarkable success.

9. CN Railway Crossing, Newcastle, Ontario

Project specifics. This grouting project was the result of a careless tunnelling operation (auger boring) below the main railway line connecting Toronto and Montreal. Substantial amounts of soil were lost during the auger boring through a sand fill, containing boulders. The tunnel was located slightly below the water table. Voids are believed to have migrated to the horizon above the water table, accumulating into one large void, which eventually collapsed causing disturbance in the embankment throughout a 30 m diameter settlement trough. As a result of the vibration caused by the railway traffic a sinkhole appeared between the tracks causing a near derailment. The very cold weather prevented a disaster.

The grouting program. Emergency grouting program to restore the integrity of the railway embankment was promptly implemented: Fast setting water reactive, hydrophobic, MDI based polyurethane resin was injected in the sinkhole to prevent further deterioration and to allow the train traffic to continue.

Remedial measures were executed in two phases, involving the injection of the embankment using regular and microfine cement grouts and rigid hydrophobic polyurethane based grouts via sleeve pipes:

The first phase was an emergency stabilization program, whereby cement and polyurethane based grouts were injected through inclined sleeve pipes to provide a quick stabilization of the most disturbed zone. It was followed by a thorough permeation grouting program utilizing microfine cement based suspension grout.

The second phase entailed the construction of a roman arch of grouted soil above the remaining portion of the tunnel trajectory, via horizontal sleeve pipes, to allow for safe completion of the tunnel construction from the other side of the embankment, with an oversized tunnel, meeting the existing tunnel below the embankment.

Effect of treatment. Long term monitoring results (inclinometers and settlement points) show that the embankment and tunnel have demonstrated permanent stability since the grouting operation.

10. Big Walnut Sanitary Trunk Sewer Extension, Columbus, Ohio

Project specifics. Tunnelling through a short "sand infilled valley" required soil treatment utilizing permeation grouting prior to tunnelling to prevent settlement of the road above and to cross this short soil infilled valley between the rock formations on both sides of the valley.

Grouting program. The pre-excavation grouting program consisted predominantly of a permeation grouting and some permeation in conjunction with hydrofracturing. Five rows of vertical sleeve pipes were used to create a Roman arch of grouted soil above the future tunnel trajectory as shown in Figure 6.

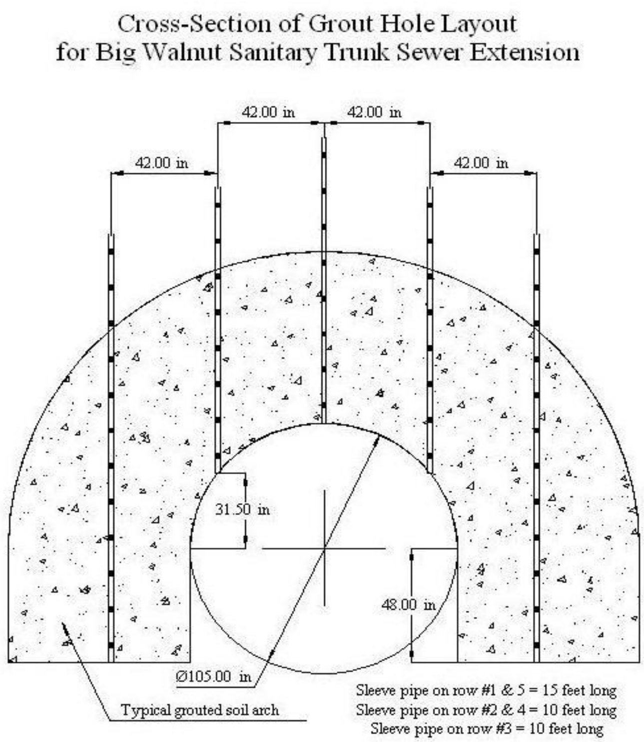

Figure 6

On this project, a permanent inexpensive sodium silicate grout was used. The tunnelling contractor, under the direction and hand-on supervision by the Engineer performed the grouting program. This program consisted of several passes of multiple hole grouting using predominantly sodium silicate grout and some hydrofracturing with cement based suspension grouts.

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