Stabilization of Running Granular Soils in TBM Alignment with Sodium Silicate Grout

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ABSTRACT: During the tunnel boring machine (TBM) excavation of the Portsmouth Forcemain Segment 2, in Portland, Oregon, the Lovat TBM encountered free flowing granular material including cobbles and boulders which resulted in excessive ground loss. Prior to stopping the TBM, the uncontrolled ground loss had resulted in a chimney opening up to the ground surface 24.4 m (80 ft) above the tunnel crown. Previous attempts at using polyurethane grouts from the face of the machine had been unsuccessful in controlling the ground loss associated with tunnel advancement. The tunneling contractor selected a grouting proposal which ultimately relied on sodium silicate grouting to stabilize the loose granular soils above the water table with an array of vertical and battered sleeve port pipes installed from a walking trail on the slope above the TBM. Drilling methods included a casing advancement system to deal with the expected cobbles and boulders in the tunnel alignment. Significant grout losses occurred in the previously loosened soils near the machine during placement of the cement-bentonite backfill grout around the sleeve port pipes. Following completion of the grouting program a 20.7 m (68 ft) length of the tunnel alignment was stabilized and the machine was advanced 12.2 m (40 ft) without measurable ground loss into a safe zone where the TBM was replaced with an open shield machine better able to deal with the boulders and cobbles in the alignment without excessive ground loss.

INTRODUCTION

A Lovat tunnel boring machine (TBM), with a 2.7 m (8.7 ft) diameter soft ground, non-pressurized cutter head equipped with a combination of shovel and bullet teeth, was selected to bore the CSO tunnel for segment 2 of the Portsmouth Forcemain in Portland, Oregon. This machine encountered unexpected boulders, during the launch. Attempts to continue advancement of the machine consisted of alternating the direction of the cutter head until the boulder was caught in the door of the cutter head where it was broken with a chipping gun. These efforts resulted in significant ground loss as free flowing sand, above the water table, ran into the machine during the process of catching and removing the boulder. Polyurethane grouts, were injected into the soil from the face of the TBM, in an unsuccessful effort in stabilizing the granular material. This was due in part because the machine was not configured for advance grouting, so only a limited portion of the face could be treated from the TBM. The polyurethane grouting operation was also negatively impacted by the significant ground loss that had already occurred. Ultimately, advancement efforts were stopped when an opening in the ground surface 24.4 m (80 ft) above the tunnel crown appeared. The contractor, under the direction of the owner, solicited proposals to use a sodium silicate based grout, which would be injected from the ground surface above the machine, as a means for stabilizing the loose granular material. With the TBM stopped under a steep hillside, just 42.7 m (140 ft) from the launch shaft, the chemical grouting contractor faced several challenges.

PROJECT OVERVIEW

To perform the chemical grouting the tunneling contractor provided a work bench in the hillside directly above the TBM. The small access area required that the contractor install battered pipes in order to reach the 20.7 m (68 ft) long target grout zone. Sleeve port pipes (SPP) and straddle packers were used as the method for injecting the chemical grout into the granular material. The layout for the sleeve port pipe installations consisted of 27 primary and secondary grout points, as well as 27 tertiary grout points, as shown in Figure 1. After installing and grouting the 27 primary and secondary holes, four of the tertiary SPP were installed and water tested to determine if the tertiary grouting was necessary. The water results indicated the need for the tertiary grouting.

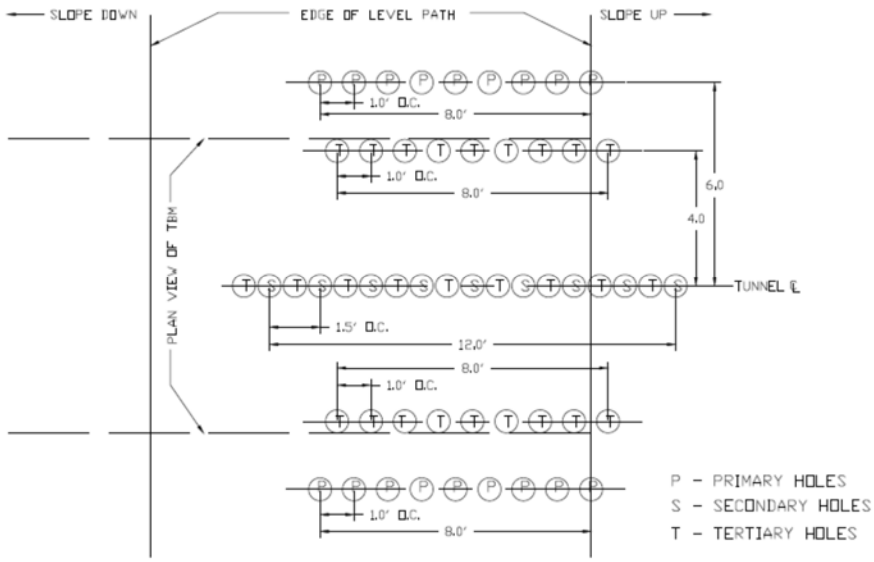

FIG. 1: Plan View of Grout Hole Layout at Work Bench

DRILLING

All equipment access to the work area was a city street, which intersected the walking trail approximately 91.4 m (300 ft) from the drilling location. To prevent the degradation of the walking trail under the tracks of the drill rig, cane mats were positioned between the rows of grout holes. Water was also channeled to one location in the work area, where piping carried it down the hillside and into a baker tank, at the bottom of the slope. Figure 2 shows the drilling operation as it is being performed on the work bench.

FIG. 2: Work Bench

The drilling was performed using a Klemm 806-3, and 0.15 m (6 in) diameter casing. Drilling depth extended down to the spring line of the tunnel, 29.3 m (96 ft) below the working grade. The battered holes that were drilled are illustrated in Figure 3. These holes extended through the entire 20.7 m (68 ft) long grout zoned. The drill mast was aligned using a total station for azimuth and a digital level for inclination to ensure the proper direction and angle of each grout hole.

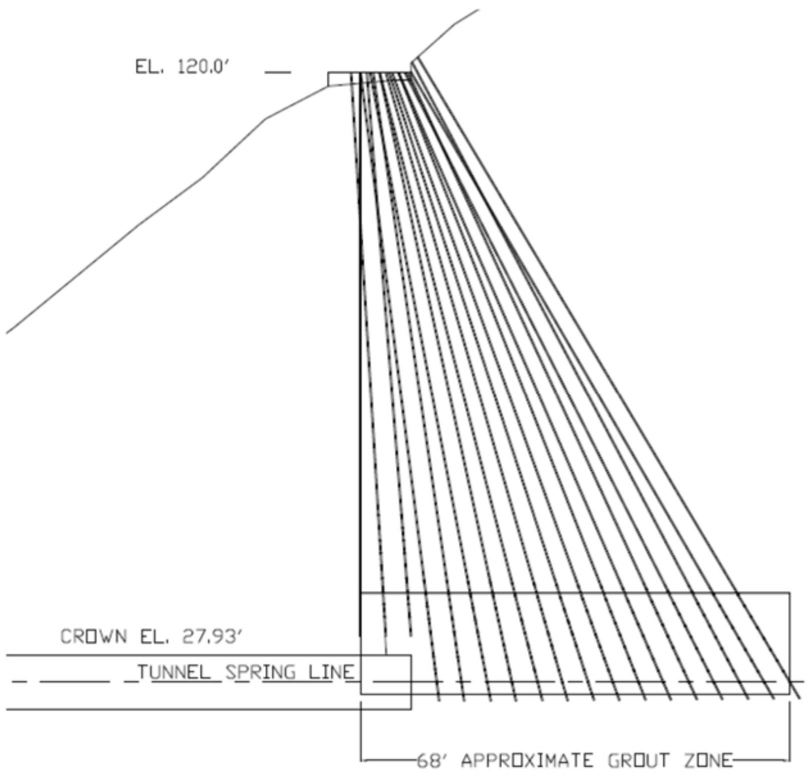

FIG. 3: Elevation View of Grout Hole Pattern

INSTALLATION OF SLEEVE PORT PIPES

The grout was injected with the use of sleeve port pipes (SPP) constructed of .04 m (1-1/2 in) PVC. Eight sleeve ports were located on each pipe at 0.6 m (2 ft) on center through the grouting zone, the first port being 0.9 m (3 ft) from the bottom of the pipe. Once the drilling had reached final depth, the SPP was lowered into the drill casing. A low strength cement bentonite grout was then placed in the drill casing around the SPP with a tremie, while drill casing was incrementally being pulled out as the grout level rose.

Given the open work nature of the soils which existed in part due to the loss of material associated with earlier tunneling and in part due to the original nature of the soils, significant cement bentonite grout consumption occurred during the installation of some of the sleeve port pipes. It was recognized that the grout take in excess of the theoretical grout volume required to fill the drill hole was filling voids. While this grout was stabilizing the loose gravels and possibly filling voids from the tunneling, which was the intent of the grouting program, it was also recognized that the excess spread of the backfill grout might inhibit the flow of the subsequent sodium silicate grout injections. However, it was believed that if there were larger voids it was more beneficial to the project to fill them with cement bentonite grout than sodium silicate grout. First, the cement bentonite grout is a more economical solution. Second, the cement bentonite will not exhibit shrinkage, but sodium silicate gel is known to shrink after curing, which could defeat the purpose of the grouting in open gravels and cobbles.

SPP GROUTING METHOD

Sleeved port pipes also known as tube a manchette pipes or TAMs provide access for the controlled injection of the sodium silicate grout. The SPPs were constructed by drilling four holes around the circumference of the PVC pipe and covering them with a rubber sleeve which prevented the backfill grout from entering the pipe and also acted as a one way valve during grout injection as shown in Figure 4.

FIG. 4: Typical Sleeve Port

Prior to grout being pumped through the sleeve port. The low strength grout in the annulus around the SPP needed to be cracked opened or fractured to allow subsequent sodium silicate grout injections. The straddle packers were lowered into the SPP, centered over the sleeve port, and inflated with water. Typically, the packers were inflated to approximately 13.8 bar (200 psi) although higher pressures were required at times depending on the injection pressure required to fracture the excessive quantities of low strength grout in the annulus and surrounding formation.

FIG. 5: Typical Straddle Packer

With the sleeve port isolated above and below by the inflated straddle packers (Figure 5), a pressure washer capable of reaching pressures of 51.7 bar (750 psi) was hooked up to the injection line of the packer. Applying pressure to the sleeve port expanded the rubber sleeve and fractured the cement bentonite grout surrounding the sleeve port pipe, creating a path for the grout to follow subsequently.

GROUTING

Sodium silicate itself does not gel and form a grout. It requires an acidic reactant to set it off. The reactant type and quantity that is chosen, as well as the dilution of the sodium silicate, will affect the time it takes for the grout to set off and gel up. Based on the application, the desired reactant time can vary greatly. For this soil stabilization application a 60 minute workability time was desired to allow the grout to flow through the voids in the soil material and completely saturate the target zone before it began to gel and lose its fluidity. An organic reactant was used to mix with the sodium silicate to form the grout. It was important in this application to have a longer working time to allow the material to move through the soil and to prevent the packers and sleeve port pipes from clogging up. On the other hand, however, it was also important not to have too long of a working time. This is because, the soil on the Portsmouth Forcemain project was a sandy granular material, and if the grout was given much longer than 60 minutes to begin to gel the contractor runs the risk of the material flowing out of the targeted grout zone.

The setup for the Portsmouth grouting was a challenge given the steep hillside and the narrow work platform. It was important to minimize the amount of equipment and material on the working platform to maximize the working space. The sodium silicate was held in a tanker that was parked at the top of the hill and gravity fed down the hillside to the grouting location. Likewise, the reactant was stored at the top of the hill and pumped directly from the storage totes down the hillside. Both the sodium silicate and the reactant were mixed with water in the appropriate proportions and held in separate totes in the back of a box truck (Figure 6) at the grouting location. The box truck contained a dual piston pump, for mixing and pumping the grout, as well as flow meters and pressure gauges to monitor the grouting. Grout was pumped from the totes, that received that material from the top of the hill, through the valve bank and then into the ground through a straddle packer. The grout mix for this project contained 45% water, 40% sodium silicate, and 15% reactant, by volume. There were four totes in the back of the grout truck for batching and pumping the grout. Two of the totes would receive the material from the top of the hill for mixing with water and the other two would feed the material into the pump for placement.

FIG. 6: Grout Truck and Dual Piston Pump

The sodium silicate was mixed with water in the first receiving tote to create a 40% sodium silicate and 10% water solution which was transferred to the sodium silicate feed tote (Tote A). The reactant was mixed with water in the second receiving tote to create a 15% reactant and 35% water solution which was transferred to the reactant feed tote (Tote B). The solutions in Tote A and Tote B were then pumped and mixed together in a single grout line to form the activated chemical grout as illustrated in Figure 7.

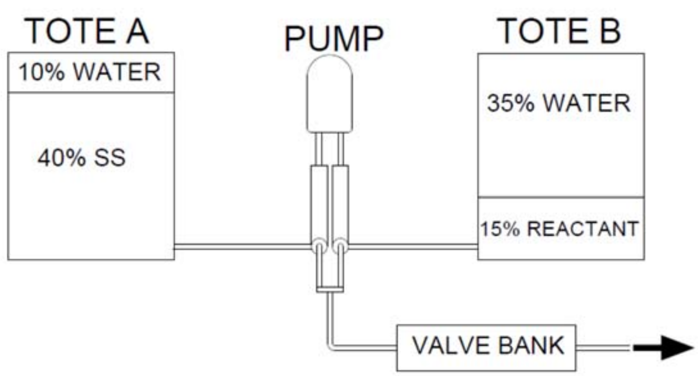

FIG. 7: Mixing and Pumping Configuration for Sodium Silicate Grouting

The grout was pumped through a valve bank that split the grout flow into multiple lines, allowing for as many as five sleeve ports to be grouted simultaneously. The valve bank also contained flow meters for tracking the volume of material as well as the pressure contained in each of the grout lines. The target volume at each of the sleeve ports was 0.4 cubic meters (14 cuft), based on a 30% void ratio and a grout spread of 0.8 m (2.75 ft). Grouting began at the bottom sleeve port, at the spring line of the tunnel, and moved up incrementally until all the ports had either achieved the target volume, exceeded a pressure of 0.7 bar (10 psi) above residual fracture pressure, and sustained flow less than one gallon per minute, or grout was seen either returning to the surface or leaking into the TBM.

RESUMPTION OF TBM DRIVE

The initial grouting proposal had been to stabilize the entire face of the TBM alignment. However, during the planning stage of the grouting, the client requested that the target grout zone be shifted upwards so that the stabilized soil would extend from just below the spring line of the tunnel to several feet above the crown of the tunnel. The thought behind this change was that increasing the height of the stabilized zone above the crown would further decrease the chance of another chimney forming from ground loss without increasing the overall cost of the grouting. When the TBM drive was resumed through the grouted zone, the presence of untreated soil beneath the spring line resulted in TBM steering difficulties. With the difference of composition between the grouted soils above the spring line and the native soils beneath the spring line, the TBM tended to drift lower with advancement. This tendency was addressed by overcorrecting the TBM steering for the remainder of the drive through into the grouted zone.

It was decided that to complete the remainder of the 1,829 m (6,000 ft) long tunnel the current TBM would be replaced with an open face digger shield. It was determined that changing the TBM would be more cost effective and less disruptive then grouting the entire length of the tunnel, which ran underneath a four lane road in front of the University of Portland. Since the original TBM had only traveled 42.7 m (140 ft) from the launch shaft, instead of constructing a rescue shaft, a steel casing was jacked over the installed liner and the original TBM from the launch shaft. With the casing in place, the original TBM was removed and replaced with a Herrenknecht open face digger shield, equipped with an excavator arm. This new TBM was successful in completing the 1,829 m (6,000 ft) CSO tunnel.

CONCLUSIONS

Sodium silicate grout proved to be a viable solution for stabilizing the granular free flowing material at Portsmouth Forcemain in Portland, Oregon. The TBM was successfully able to advance 12.2 m (40 ft) to a safe zone, were it was replaced with and open face shield equipped with an excavator arm, breasting plates and a sand table which helped prevent the inflow of excess material and made it easier to remove large boulders. The SPP grout injection method provided control of the grout placement, ensuring full grout coverage through the target zone.

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