GROUTING TO MINIMIZE SETTLEMENTS PRIOR TO TUNNEL EXCAVATION – A CASE STUDY

Douglas, M. Heenan[1], P.Eng., Member, ASCE and Michael Xu[2], Ph.D., P.Eng.

ABSTRACT: Phase I of the Glen Echo Creek Culvert Reconstruction Project, involved lowering the invert of an existing concrete arch tunnel along with replacing an existing corrugated metal pipe (CMP) with a new tunnel between 28th and 29th street in Oakland, California. All construction work was performed within the tunnel by hand mining techniques. Due to the close proximity to residential buildings, roadways and utilities, various grouting techniques were applied to minimize ground settlement, stabilize subgrade soils and reduce water seepage to facilitate hand excavation. This paper describes the design and execution of the various grouting programs implemented, as well as the grouting performance.

INTRODUCTION

Glen Echo Creek flows through the City of Oakland, California. Channel hydraulic investigations indicated that the 25-year and 100-year storm events would cause short term, but widespread flooding along certain sections of the creek. The County of Alameda Public Works Agency, therefore, decided to conduct several improvements to the creek system. This project was a portion of Phase I the Glen Echo Creek Culvert Reconstruction Project, and involved lowering the invert of a concrete arch culvert tunnel and replacing an existing

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[1] Vice President, Advanced Construction Techniques Ltd., 10495 Keele Street, Maple, Ontario L6A 1R7

[2] Geotechnical Engineer, Advanced Construction Techniques Ltd., 10495 Keele Street, Maple, Ontario L6A 1R7

2.1 meter diameter CMP with a 3 meter diameter tunnel between 28[th] and 29[th] street, which is about two blocks east of Broadway in Oakland.

The existing concrete arch tunnel extended from station 23+99 to 26+76, was 85 m long with inside dimensions of 2.4 m high by 2.1 m wide was to be lowered by 0.9 m. The work in this section included removal of the existing concrete invert and subgrade materials and construction of new reinforced cast-in-place sidewalls and invert. Hand mining methods were used to perform the excavation work and grouting techniques were utilized for temporary support.

The existing 2.1 m diameter CMP extended from station 22+92 to 23+96, was 31.7 m long and was also to be lowered by 0.9 m. A small backhoe was used to remove the existing CMP. The open excavation was initially supported by stabilizing the ground using grouting techniques, followed by the installation of circular steel plates. The final support system consisted of a reinforced shotcrete lining.

SITE CONDITIONS AND GEOLOGY

There are several roadways, parking areas and numerous structures that are located adjacent to the culvert alignment as shown in Figure 1. Several one and two-story residential buildings are positioned along the west side of the alignment. Houses in close proximity to the culvert include a two-story wooden home at 4.6 m west of station 22+90 and a one-story home 3.0 m west of the culvert, between stations 24+80 and 25+70.

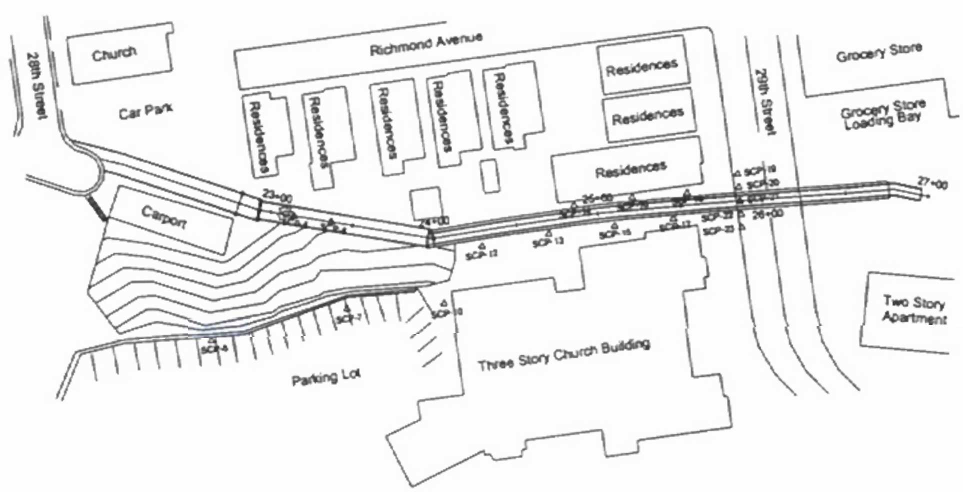

Figure 1. Site layout of line B improvement, Oakland.

A typical section at station 25+50 is shown in Figure 2. A three-story church was located 3 m to 6 m east of the culvert between stations 24+90 and 25+60, and the cross section of the structure relative to the tunnel alignment is shown in Figure

2, as well. An asphalt paved parking area associated with the three-story church overlaid the concrete arch section between stations 24+90 and 25+70. The alignment was intersected by 29th street that runs perpendicular to the project centerline at station 26+00.

The ground surface adjacent to the culvert alignment generally slopes east to west at a relatively moderate grade. Between stations 22+80 and 24+10 the culvert alignment is situated near the toe of a steep embankment fill slope to the east. This embankment supports a parking lot of the three-story church at about elevation 17.8 m. An asphalt drive/parking area associated with a small church to the east contains a carport canopy and is situated approximately 3 m east of station 22+80. A 1.4 m (4.5 ft) diameter tree is positioned near the slope toe and directly over the culvert at station 23+10.

Geotechnical investigation adjacent to the tunnel alignment indicated that the overburden materials above the CMP section consisted of silty sand and clayey sand fill, and then varied from clayey sand, silty sand, sandy clay to clayey gravel. At station 25+90, boring logs indicated that the top of overburden consisted of stiff silty clay fill to a depth of 4 m below ground surface.

Medium stiff to stiff silty clay with sand was present below the fill to a depth of approximately 7.9 m. The borings cored through the walls of the arch culvert encountered sandy clay and silty clay fill at the upstream portion of the culvert from station 26+55 to 25+34, and encountered silty sand from station 24+79 to 24+14. The borings cored through the floor of the arch culvert encountered sand and gravel. The grain size distributions of the subgrade soils are shown in Figure 3, indicating that the soils are not fully permeable at the top of CMP, and partially permeable at the invert of CMP and Arch tunnels.

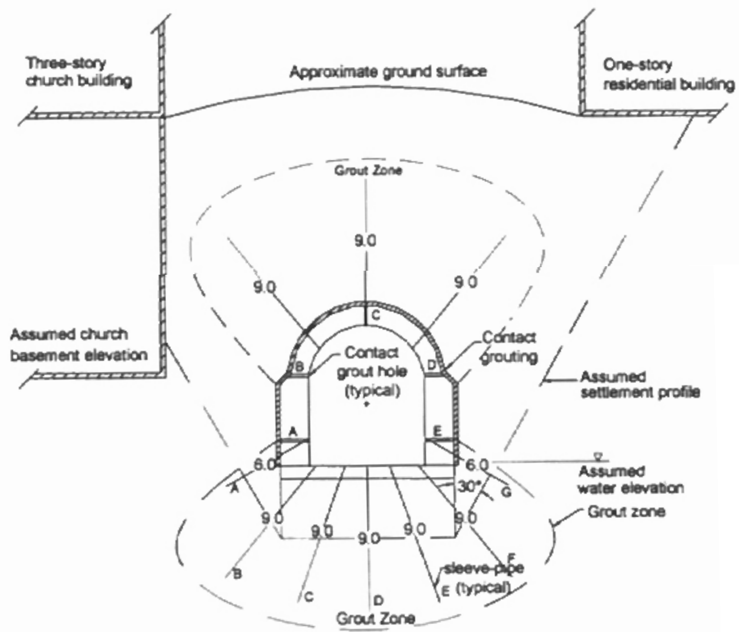

Figure 2. Typical layouts of grout pipes at station 25+50.

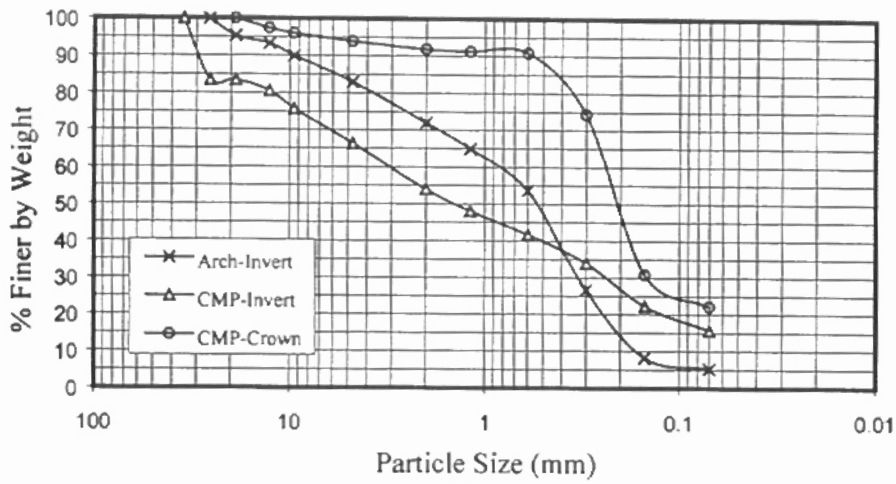

Figure 3. Soil particle size distributions.

DESIGN AND EXECUTION OF GROUTING PROGRAM

The grouting program was a design-build type of construction with performance based criteria. The main objectives of the grouting programs were:

1. To prevent settlement of buildings, utilities, and roadways in close proximity to the arch tunnel by means of ground stabilization.
2. To stabilize subgrade soils to facilitate open excavation.
3. To mitigate water seepage during hand mining operations.

To accommodate the above objectives, the following grouting programs were designed and performed at various locations in conjunction with different construction sequences.

Contact Grouting of Arch Culvert Concrete Tunnel

Given that the existing tunnel was more than 50 years old, it was anticipated that voids may exist directly above and beside the concrete arch walls and the concrete arch structure/soil interface. Contact grouting would provide a positive contact around the structure, resulting in reduced surface settlement while providing grout containment for the subsequent permeation or fracture grouting operations. Contact grouting was performed prior to any other grouting techniques.

The typical patterns of contact grout hole alignment are shown in Figure 2. Five 63.5 mm diameter holes, designated as A, B, C, D and E, were drilled through the concrete lining at a 1.2 m spacing along the alignment of the tunnel. Sequencing of the grouting operation was A, E, B, D, then C. Mechanical packers were installed and a neat cement grout was injected through the packer until a connection was established with adjacent holes or until a refusal pressure of 69 kPa was achieved.

During the contact grouting operation, extensive grout seepage occurred through the concrete structure at several locations. When excessive seepage was encountered grout injection was momentarily stopped, and fast setting hydraulic cement was used to seal off the excessive seepage and the grouting operation was then resumed. The total grout volume injected was 61 m^3, which exceeded the grout volume anticipated.

Pre-conditioning (Compensation) Grouting

Compensation grouting was to be performed during excavation in order to mitigate ground settlement caused by the hand excavation. This grouting was to be initiated by ground movement as indicated by surface monitoring. Three holes were drilled through the concrete tunnel lining at 1.2 m spacing. Custom fabricated 38.1 mm diameter steel sleeve pipes were then jacked into the roof at the arch tunnel, according to the alignment shown in Figure 2. Compensation grouting was not specified for the CMP, but was performed using a single sleeve pipe at the center of the roof (refer to Figure 2) in order to control the ground settlement due to shallow overburden coverage and close proximity to residential buildings.

Pre-conditioning grouting was carried out prior to permeation grouting and tunnel excavation at the arch tunnel, and was carried out simultaneously with the permeation grouting at the CMP. This operation was intended to condition the insitu soil prior to excavation to prevent large sudden settlements due to the existence of voids and loose soil. Ground heave was monitored during the pre-conditioning grouting. A limited amount of cement grout was injected at the concrete arch tunnel due to concerns of heaving the nearby structures. A considerable amount (19 m^3) of neat cement grout was injected at the CMP.

Soil Stabilization – Permeation and Fracture Grouting

As indicated by the soil particle distribution, the underlain soils were partially permeable at the invert of arch and CMP. The soil stabilization grouting was actually a combination of permeation and fracture grouting. Permeation and fracture grouting program was designed and performed, in order to stabilize the subgrade soils and facilitate lowering the culvert invert of the arch concrete tunnel, and the enlargement of the CMP. Sodium silicate solution grout was chosen for the intended purpose.

Typical grout hole layouts for the permeation/fracture grouting are shown in Figure 2. A series of holes designated as A, B, C, D, E, F and G were drilled through the floor slab and sidewalls of the arch culvert and CMP. Then various lengths of 38.1 mm diameter steel sleeve pipes were jacked into the pre-drilled holes to develop adequate grout zone coverage. After each sleeve pipe installation, the annular space between the steel pipe and floor slab was sealed for grout containment. The spacing for each array was 2.1 m along the tunnel alignment. Mechanical packers were used to seal individual sleeves with the grouting injection sequence proceeding from the side walls to the middle of the tunnel invert as A, G, B, F, C, E then D.

A sodium silicate grout plant (refer to Figure 4) was custom designed and commissioned for mixing and pumping the sodium silicate grout. A grout delivery system was installed throughout the tunnel with a header system used at point of placement. The grout plant was located outside the tunnel at the east end portal lay down area. The grout injection system consisted of a piston type two component pump with a 1 to 1 ratio. The hardener was pre-mixed with water as component A, and the sodium silicate solution as component B. Components A and B were pumped separately to the point of injection and combined at the header in a static in-line mixer prior to entering the soil.

The sodium silicate used was an N-grade silicate. It has a silica to soda ash molecular ratio (SiO_2/Na_2O) of 3.22. The silicate is composed of 28.7% SiO_2 and 8.9% Na_2O and has a density of 41°Be at 20°C, a specific gravity of 1.39, a viscosity of 177 cp at 20°C, a pH of 11.3, and solids of 37.6%. The hardener used was a Dibasic Ester (DBE) solution. The DBE is composed of 21% dimethyl adipate, 59% dimethyl glutarate, and 21% dimethyl succinate.

During the initial phase of the project, it was observed that the sodium silicate grout was not setting within the soil mass in a predictable manner. A quick set grout was required due to flowing ground water conditions. The sequencing of excavation immediately after grouting as well as ground water conditions required a modification to the grouting method in order to accelerate the setting time of the sodium silicate solution. This was facilitated by the injection of a cement based grout.

The silicate based cement grout or cement based silicate grout have been used widely for applications where accelerated setting time of the injected grout is required (Shroff and Shah, 1992; Liao et al. 1992). The modified permeation/fracture grouting method differs from the traditional Joosten process and overcomes many disadvantages of this method. The Joosten process involves injecting concentrated sodium silicate into one hole and a strong calcium chloride solution under high pressure into an adjacent hole (Karol 1990). When a sodium silicate solution and a concentrated solution of appropriate salt are mixed, the reaction forms an instantaneous gel. The Joosten process results in a strong gel, if properly used. However, the high viscosity of the solution and the need for many closely spaced grout holes limits the use of this method. Also, the nature of the process prohibits a complete reaction of the two liquids (Karol 1990).

The modified grouting operation involved multiple injections with a limited volume of grout material injected during each cycle, to facilitate a complete reaction of the two liquids. Mechanical packers were set near the top of the sleeve pipes and a predetermined volume of sodium silicate grout was injected into each hole according to the injection sequence. The sodium silicate grout was then immediately followed by injecting a predetermined volume of cement grout to accelerate the set of the sodium silicate grout. After all holes along a segment of tunnel had been injected (typically 6 to 10 m), a second cycle of injection was performed with a

Figure 4. Sodium silicate grout plant.

lower packer setting and higher injection pressures. This process was repeated until a predetermined total volume of grout for each section was reached or until the maximum injection pressure was reached with no flow.

The arch invert tunnel was divided into 69 sections, each covering 1.2 m of the tunnel. As a result of a stringent construction schedule, the excavation had to be preformed at five locations simultaneously. In order to provide stabilized soil for the open excavation, the grouting work was divided into 10 segments. Initially, 5 segments with 5-6 sections each were grouted at odd locations, with excavation proceeding with the 5 grouted segments. The remaining 5 segments, typically 8 sections, were grouted later along with the excavation. Figure 5 shows the grout volume injected at the arch tunnel. The average grout take is approximately 1.7 m^3 and 0.7 m^3 of sodium silicate grout and cement grout, respectively. It was observed during all excavation that the soils remained stable and no soil losses occurred.

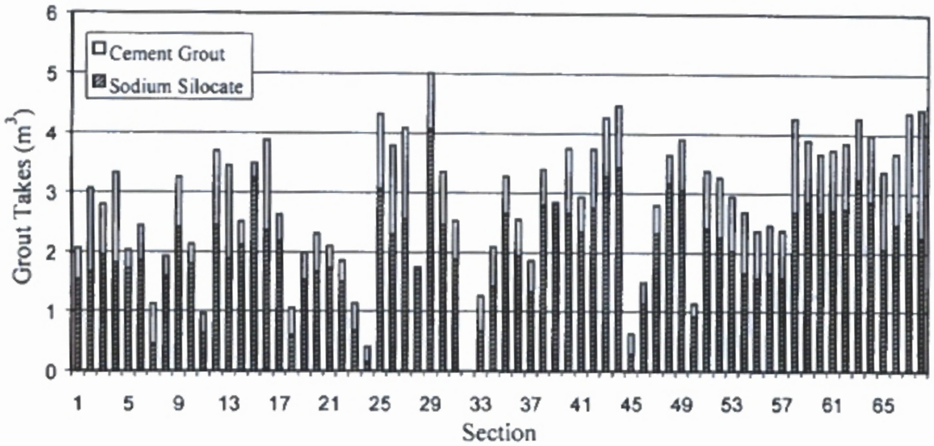

Figure 5. Permeation grout takes at Arch tunnel.

At the CMP, permeation/fracture and compensation grouting were carried out simultaneously as shown in Figure 6. Figure 7 shows the grout takes at the CMP, with an average of approx. 2 m^3 and 1 m^3 of sodium silicate grout and cement grout, respectively. After completion of all grouting work at the CMP, the excavation was started. It was observed that there was no soil loss occurring and the grouted soils were very stable, as shown in Figure 8. As a result, the open excavation could be carried out with longer segments during each cycle without the need of temporary support, typically 5.5 m, as compared with anticipated 1.8 m per cycle.

Figure 6. Permeation/fracture grouting and compensation grouting at CMP.

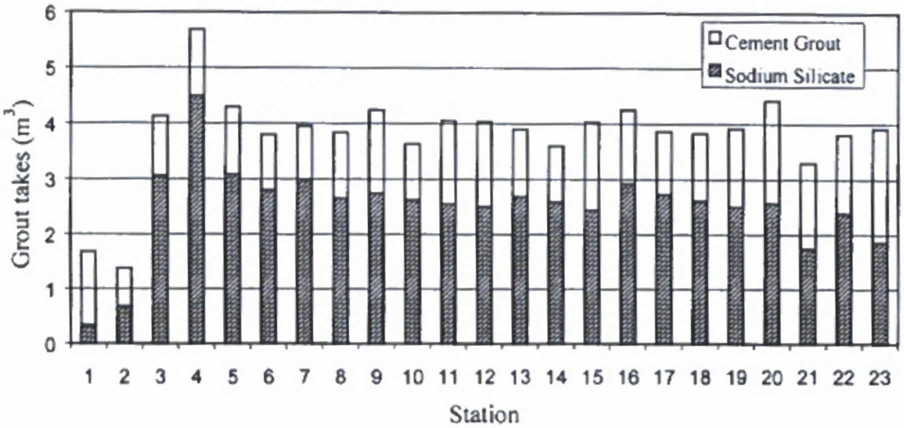

Figure 7. Permeation/fracture grout takes at CMP.

GROUTING PERFORMANCE

Prior to and during grouting and excavation, elevation changes of ground surface, buildings and sub-grade soil were closely monitored using various monitoring techniques. The layouts of surface control points are shown in Figure 1. The ground movements at Arch and CMP are shown in Figures 9 and 10.

Figure 8. Exposed soil surface after excavation at CMP.

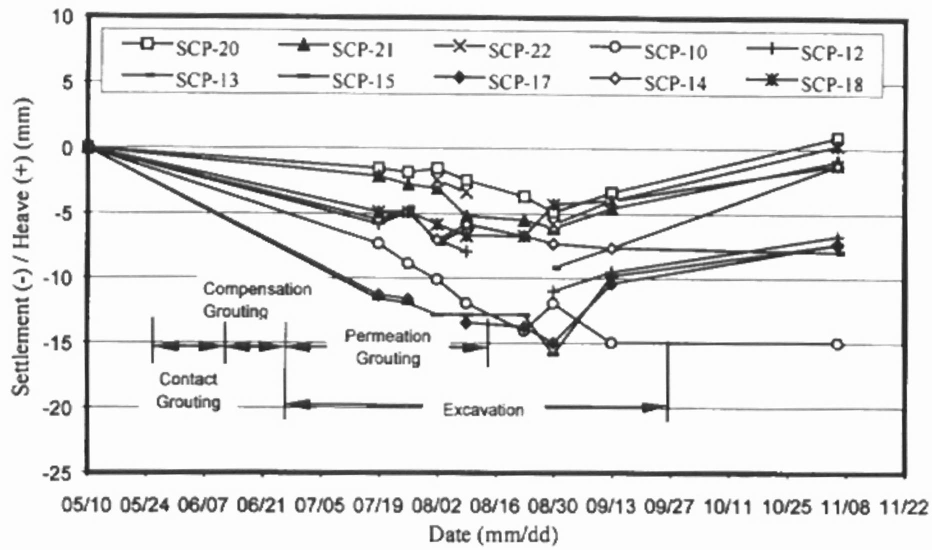

Figure 9. Movements during construction at Arch tunnel.

As indicated in Figure 10, the maximum ground settlement was 15.8 mm during construction at SCP-15 and 8 mm after construction at SCP-13 on the East side of the tunnel, in close proximity to the three-story church. The maximum ground settlement was 10 mm during construction and 3 mm after construction at SCP-16 on the West side of the tunnel. The maximum settlement on the roadway was 6 mm. No damage to the adjacent buildings were observed or recorded.

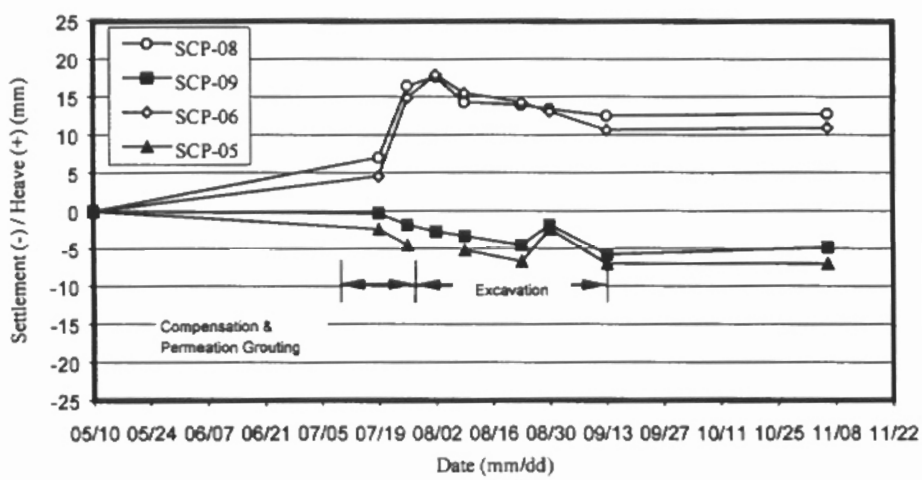

Figure 10. Movements during construction at CMP.

A maximum ground heave of 18 mm was intentionally created at the crown of CMP, which then settled to 12 mm after construction. A maximum settlement of 15 mm was observed at SCP-10 on the parking lot, and 7 mm at SCP-05, which was farther away from the CMP. No damage to adjacent buildings or roadway was observed or recorded.

Conclusions

The various grouting programs developed and instituted for the project were successful in minimizing ground settlements and facilitating open hand excavation. The grouting techniques utilized were practical and suited the site specific conditions, allowing the project to be completed on schedule. As is the case with most grouting projects, modifications were made to original grouting plans to best suit the existing site conditions.

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