Geotechnical Aspects of Underground Construction in Soft Ground, Mair & Taylor (eds)
© 1996 Balkema, Rotterdam. ISBN 90 5410 856 8

The use of jet grouting to improve soft clays for open face tunnelling

G. Pellegrino
Rodio S.p.A., Milan, Italy

D. N. Adams
Jacobs Associates, San Francisco, Calif., USA

ABSTRACT: The Islais Creek Transport/Storage Project is part of the sewer system upgrading program under construction in the San Francisco Bay area. Jet Grouting was successfully used to pretreat soft marine clay for open face tunneling. The project was originally designed to be constructed under compressed air. This project was the first recorded use of full face jet grouting for tunneling in soft clay.

1. PROJECT DESCRIPTION

1.1 *General description*

In order to reduce overflows of combined untreated sewage into the Bay, the City of San Francisco implemented an extended program of improvement of the sanitary and storm sewer system. The plan involves the construction of new sewer lines, storage and transport facilities and treatment plants.

The Islais Creek Transport/Storage System will collect and store the excess flows for later treatment at the City's Southeast Treatment Plant, prior to discharging into the Bay.

1.2 *Contract "E"*

Contract "E" is the lowest portion of the Islais Creek System, which feeds combined sewer overflows to the treatment plant. The project, approximately 350 meters (m) in length, consists of the following main features: The 156 m long 4.6 m diameter Davidson Tunnel, the 76 m long 4.1 m diameter Undercrossing Tunnel, and the Transport Storage structures which combined are 110 m of open cut sewer boxes.

The Davidson Tunnel is located adjacent to and under many structures, including an active 1.8 m diameter sewer, the 7.5 m wide by 10.4 m deep Davidson Box Sewer, water, gas, telephone and high voltage electric lines, and several surface structures.

The Undercrossing Tunnel crosses under the City's 1.7 m diameter soil-supported Force Main, Interstate Highway 280 (three viaducts), the Commuter Rail/Amtrak railroad tracks (RR Embankment), and several electrical and fiber optic utilities.

The 91.5 m West Transport/Storage (T/S) box sewer crosses under and connects at two locations with the City's existing three compartment box sewer. The 18.5 m East T/S box structure connects to the Davison Box Sewer and is sized to serve as the tunnel access shaft.

The finish invert elevation ranges across the project from 12.8 to 14.3 m below the ground surface, with maximum excavation depths of up to 15.2 m.

2. GEOLOGICAL SETTING AND GEOTECHNICAL FEATURES

Prior to the end of XIX century, the site area contained an embayment surrounded by tidal marshland. A land reclamation operation took place in the 1930s, and most of the area was filled with 3 to 6 m of sand, rock fill and miscellaneous waste.

The soil formations relevant to the design and construction of the project are Fill and Bay Mud.

FILL: As a result of its nature, the characteristics of this layer are highly variable. This surface layer consists mainly of brown medium dense, poor to well graded sand and gravel, clayey sand, clayey silt and silty sand; boulders and cobbles are frequently encountered. Miscellaneous rubbish and waste are mixed with this material (a garbage dump and junk yards have been previously located in the site area).

BAY MUD: This is the most critical formation for the design and construction and underlies the project area for its whole length. It falls into the MH or CH category of the Unified Soil Classification System and can be therefore designated a plastic silty clay or clayey silt with trace of organic, shells and sand. The consistency ranges from soft to medium stiff in the upper portions of the deposit, to medium stiff to stiff in the lower portions. The upper portion (6 m) has a higher water content, liquid limit and plasticity index and a lower unit weight than the mud below. The undrained shear strength vary considerably along the project alignment as summarized in Table 1.

	S_u (kPa)	U_c (kPa)
Undercrossing Tunnel		
west side	29	2140
east side	23	2430
under embankment	48	5070
Davidson Ave. Tunnel	18	4520

Table 1: Undrained shear strength (S_u) of native Bay Mud and unconfined compressive strength (U_c) after jet grouting treatment in kPa.

Consolidation test data indicate that the Bay Mud ranges from normally consolidated to slightly over consolidated, with overconsolidation ratios ranging from 1.05 to 1.62.

Consolidation of the Bay Mud is an ongoing process in the area and is causing considerable settlements (more than 0.6 m in some areas). The zone below the railroad embankment reflects the surcharge load of the embankment itself. The embankment has and continues to accelerate consolidation of the Bay Mud underneath, resulting in settlements and an increased shear strength.

Groundwater is encountered at depths ranging from 1.5 to 2.5 m below ground surface and can be affected by tides.

3. TUNNEL DESIGN

3.1 *Original Design*

The original project design calls for tunneling to be performed under compressed air. Jacobs Associates, San Francisco, CA, designer of the project, indicated that the Face Stability Factor ($\sigma v/S_u$) ranged from 5 to 9 for both tunnel alignments. A value of 6 or more typically indicates squeezing ground conditions. They also reported that the tunnels would be driven through numerous subsurface obstructions, including timber and concrete piles. To account for the squeezing ground and the anticipated obstructions, they specified use of compressed air and a compartmentalized breast boarding shield for tunneling. The specified primary support was gasketed steel liner plates.

3.2 *Jet Grouting CICP*

Shortly after the award of the $21.7 million contract, the General Contractor, Kajima Engineering and Construction, Pasadena, CA, and their Specialized Subcontractor, Nicholson-Rodio Joint Venture, Bridgeville, PA, submitted a Construction Incentive Change Proposal (CICP) to use jet grouting to pre-treat the soft Bay Mud along both tunnel alignments, excavate the jet grouted soils with an open face road header, and install steel ribs and wood lagging as the primary tunnel lining. Jet grouting is a soil improvement technique which utilizes fluids jetted at very high pressure to fracture, partially replace and simultaneously mix soil in situ with a stabilizing agent. The proposal, based on 2-D and 3-D F.E.M. analysis, called for full face treatment, extended 1.2 meters around the excavation, as shown below in Figure 1. This mass would have a minimum

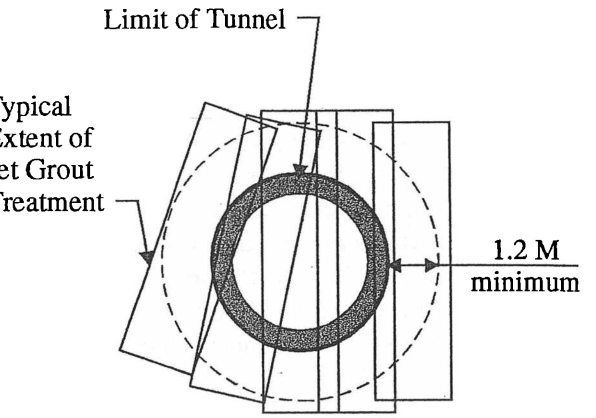

Figure 1: Cross Sectional View of Tunnel With Jet Grouting Shown

unconfined compressive strength of 830 kPa, approximately 12 times the strength of the Bay Mud, which would provide the necessary face support, and upon excavation, create a ring of support sufficient for the placement of the temporary lining. The F.E.M. analysis predicted settlements at the ground surface after tunneling on the order of 10 mm. The proposal also included construction of a Jet Grout Test Program, to confirm the Contractors' jet-grouted soil design parameters.

The City of San Francisco, recognizing the reduced risk for loss of ground, injury, and fire accepted the CICP for a gross savings of $190,000. The City's acceptance was contingent on the results of a Jet Grout Test Program (JGTP). The City's designer amended the Contractor's proposed temporary lining of steel ribs and lagging to include 9 m of bolted steel liner plate to be installed at beginning and end of each tunnel.

4. JET GROUTING TEST PROGRAM (JGTP)

4.1 *Purpose of the test*

The purpose of the JGTP was to show that jet grouted columns could be installed to create a continuous mass of treated soil into the weak clay formation; that the design strength of 830 kPa for the grouted soil could be achieved; and that heave and settlement of the ground and adjacent structures could be controlled.

The test consisted of 12 jet grouted columns installed using the Rodinjet technique and equipment. Six (6) of the test columns were single-fluid (RJ 1) and 6 were double-fluid, using grout and air (RJ 2).

4.2 *Test Description*

The test columns were installed below the fill level to depths ranging from 4.6 m to 8.5 m in two days. The exposure, examination, and sampling of the test columns required the installation of a shoring system composed of sheet piles and bracing.

An automatic batching plant was calibrated to obtain a constant water/cement ratio for the grout of 0.83 by weight, at a production rate up to 20 m^3 per hour. Type I/II low alkali cement was employed to prepare the grout mix, resulting in a viscosity of 32 Marsh seconds and a unit weight of 1570 gr/l. The U_C strength of the grout averaged 18 MPa at 7 days and 33 MPa at 28 days. A variety of grouting parameters were tested, resulting in cylinders of uniformly grouted clay.

At completion of jet grouting, a 9 m x 9 m sheet-pile supported test pit was excavated to expose the top 1.2 m of each column. Diameters ranged from 0.8 to 1 m for the single-fluid (RJ1) system and from 2.4 to 2.9 m. for the two-fluid system (RJ2). Laboratory testing (ASTM C30) on the grouted soil showed an average unconfined compressive strength of 3400 kPa for RJ1 and 1400 kPa for RJ2 samples.

Based on the test results, a grouting pressure of 400 bar was selected, together with an air pressure of 9 bar.

A conservative grout column spacing of 1.8 meters was chosen to account for the numerous subsurface obstructions. This layout resulted in 7500 meters of RJ 2 columns, with a replacement factor (volume of grout injected per volume of soil treated) of 38 %, and up to 400 kg of cement per cubic meter of grouted soil.

5. PRODUCTION JET GROUTING

Production started on the Davidson Tunnel. The 156 m stretch was grouted with 676 columns. The existing 1.8 m sewer on piles overlying the excavation alignment was underpinned by jet grouting to avoid settlements during the mining operation.

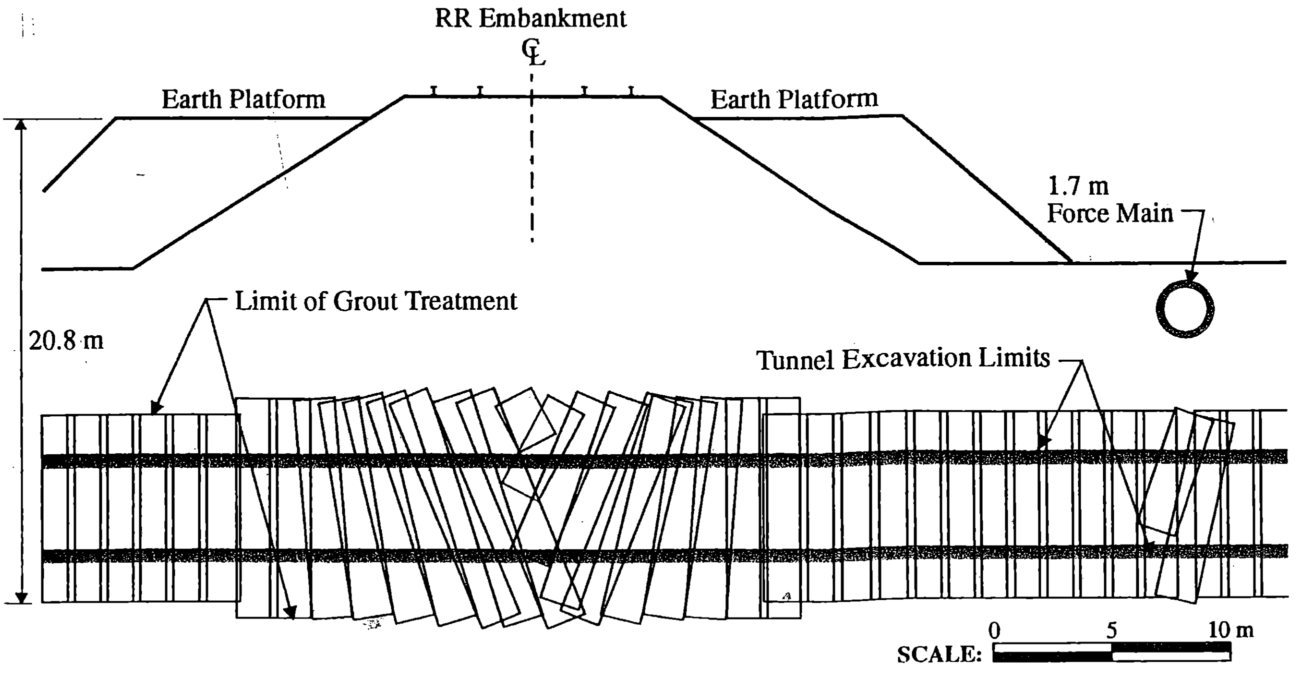

Figure 2: Profile of Undercrossing Tunnel

The operation then moved to the Undercrossing Tunnel, where treatment required installation of columns inclined up to 30° from vertical, as shown on the profile in Figure 2. The 1.7 m Force Main was heaved 140 mm during jet grouting of the first 6 or 7 jet grout columns beneath it. After a revised installation procedure was proposed and successfully tested, jet grouting resumed beneath the force main. The revised installation procedures included precutting and pretreatment of the fill. Precutting and pretreatment are used to control ground deformations. Precutting uses increased flow and pressure of fluids during drilling to maintain an open hole while jetting. Pretreatment is the systematic stabilization of the soils above the design jet grout zone to allow for drilling and jetting with continuous flow of spoils.

The installation of jet grouted columns beneath the RR Embankment required the use of a temporary earth platform on both sides of the embankment (Figure 2). The inclined columns immediately underneath the tracks were grouted through precased holes to prevent the washing of the embankment soils by the drilling fluids. The 76 m stretch was grouted with 306 columns, with no heave of the tracks.

Routine testing on the grouted mass in both tunnels showed an average unconfined compressive strength above 3500 kPa. Unconfined compressive strength test results on core samples taken in the differing Bay Mud zones along the tunnel alignments are shown in Table 1 above. RQD calculated for the cores averaged greater than 60%.

6. TUNNELING EQUIPMENT

Both tunnels were excavated with a Dosco/Terra Form open faced road header tunneling machine. The machine was made of two components - the shield, and the boom cutter. The shield assembly consisted of a front section and a tail section. The body of the front section was equipped with a 120 mm hood, a boom cutter frame, twelve 1350 kN x 1.7 m stroke thrust jacks, two hydraulic roll stabilizers, and eight 1100 kN x 0.8 m stroke breasting jacks. The tail section was equipped with a rib erector and expander, which had an expansion jacking capacity of 260 kN. A 17 m long conveyor belt brought muck from the face out over the top of a trailing frame into 6 m^3 cars, which were transported by locomotive to the tunnel shaft.

The boom cutter was ring mounted on a rail carriage and was powered by a 190 horse power Poclain MS50 direct drive hydraulic motor. It had a 118 mm cutter head with 20 drag bits located radially around it, and was capable of extending 2.3 m in front of the shield. Head rotation was 60 rpm at 32 MPa during normal operations. The torque at normal operations was 2237 kg^{-m}, with a force delivered at each bit of 58 kN. The overall length of the 4.6 m diameter machine was 5.2 m, and it weighed approximately 624 kN.

4.6 m and 4.1 m diameter shields, equipped with the same boom cutter were used to mine both tunnels.

7. TUNNEL EXCAVATION AND MACHINE PERFORMANCE

The Davidson Tunnel excavation commenced on 14 February 1995. During the first 30 working days, the tunnel advanced an average of 0.8 m per day. By April 29 the full trailing gear was installed. The remaining 129 m had an advance rate of 5 m per 10 hour shift. An average of 6.1 m per shift occurred during the last 15 shifts leading to hole through on May 8 1995.

The tunnel machine was removed from the Davidson Tunnel, and the boom cutter was re-assembled within the second 4.1 m diameter tunnel shield. Tunneling for the Undercrossing Tunnel commenced on June 22, 1995. During the first 13 work days the average advance rate was 1.5 m per 10 hour shift. After assembly of the trailing gear, the average advance rate was about 3.7 m per shift, with hole through on August 3, 1995.

Typically, the road header boom was used to cut approximately 1.2 m to 2.4 m in front of the shield, from the bottom of the face to the top. At the beginning of a typical excavation cycle muck was collected on the bottom of the shield. After excavating the bottom half of the face, mucking and excavating were simultaneously performed by the road header by feeding the conveyor with the muck cars in place. The excavated space stayed open for the entire excavation and mucking period. After the 1.2 to 2.4 m long cylindrical space was clear of muck - often an operation which used men in the "bald zone", the machine was pushed into the excavation with the thrust jacks, which reacted against the primary lining. During excavation, primary lining, typically steel ribs and lagging, were stood within the tail section of the machine. As the machine was shoved forward, the primary lining was shoved out against the previous set, which was then expanded. During the shove, machine steering was performed by varying the pressures on specific thrust jacks.

Throughout excavation of both tunnels, the jet grouted soils in the face and crown were stable. Throughout much of the Davidson Tunnel, the jet grouted soil was completely continuous. Often, the temporary lining was not fully engaged. Throughout the Undercrossing Tunnel, discontinuities in jet grout treatment occurred around timber piles. During one excavation sequence, a third of the tunnel face was "untreated" however, the clay at these "untreated" areas was very stiff and uncharacteristically dry. In no cases did instability of the face occur.

Tunnel muck consisted of chips of the jet grouted clay ranging in size from 3 to 70 mm, which behaved like siltstone or mudstone chips. Generally, muck was lifted to the ground surface and temporarily stockpiled near the shaft. During wet weather, the muck tended to become more soft in consistency. It was loaded into trucks directly from the stockpile with a standard bucket loader for off site disposal. Most of the tunnel muck was re-used by the landscaping industry. By comparison, native Bay Mud excavated during construction of the many cut and cover structures was difficult to handle and costly to dispose of.

Groundwater seepage was approximately 0.32 l/sec at the Davidson Tunnel, and 0.12 l/sec at the Undercrossing Tunnel.

A total of 41 piles were encountered during both tunnel excavations. Precast concrete piles and timber piles were broken up and removed from the face with no impact on the excavation operations. However, the wood in the tunnel muck did make disposal more difficult. In addition, at several locations, the remaining timber "stub" at the limits of the excavation complicated the steerage of the machine. At two different locations steel H-piles were encountered. These two piles did stop excavation, but stability of the jet grouted soil mass at the face made removal by hand relatively quick, resulting in very little impact on production.

During the excavation, a strong ammonia odour was typically released into the air inside the tunnel. Based on analysis of air monitoring and sampling, it was determined that during excavation, airborne ammonia concentrations ranged from 7 to 20 mg/m^3. After excavation stopped, airborne concentrations of Ammonia were reduced immediately to a range of 0.7 to 2.6 mg/m^3. Organic cartridge respirators were required to be worn during excavation, and full circulation ventilation was run continuously to the tunnel face throughout the tunnel operations. Similar conditions occurring after jet grouting in clays have been reported.

8. INSTRUMENTATION DATA

Instrumentation included surface settlement points, lateral deformation points, and inclinometers located across the entire project site. An instrumentation program was developed and implemented by Haley & Aldrich Inc., San Francisco, CA, who served as the project construction managers.

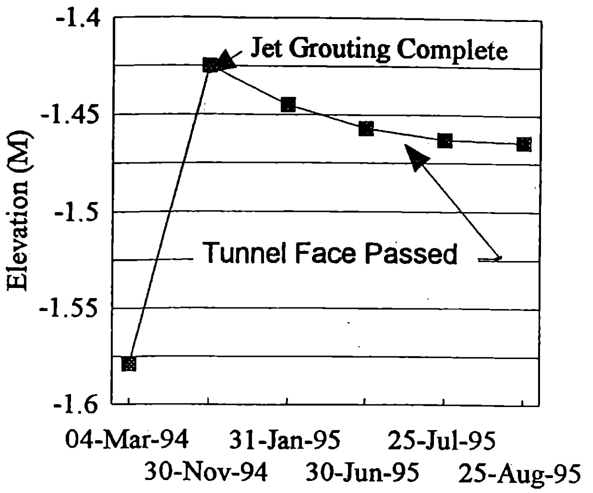

Figure 3: Summary of Settlement Data

Perhaps the most representative settlement data was obtained on the City's 1.7 m main over tunnel center line. Figure 3, above, is a plot of the elevation readings taken at this point over the project duration. The settlement which occurred after jet grouting and before tunneling is most likely due to consolidation settlement of the soft Bay Mud below the earthen work platforms and RR Embankment. Shown on the plot are significant milestones. As indicated the overall settlement of the soil supported structure since tunneling passed under it is of the order of 6 mm. This data corresponds well with other data obtained on the site. Generally along the Davidson Tunnel center line, settlements ranged from 5 to 15 mm at the 5 undisturbed settlement points.

Settlement data for the Undercrossing Tunnel is more difficult to generalize due to the use of the temporary earthen work platforms, the continuous settlement of the RR Embankment (documented prior to the start of construction), and the repeated track re-ballasting effort which destroyed settlement points. Points at the tracks which were monitored before tunneling and after completion of the tunnel lining indicate an overall settlement ranging from 12.7 to 19 mm. Other settlement points above the Undercrossing Tunnel indicate similar results.

Three inclinometers were installed within 4.6 m of the tunnel centerline after jet grouting was completed. The inclinometer data was obtained daily immediately before and after the machine passed, and then weekly when the machine was within 30 m of the instrument. The data collected, in conjunction with observations made during tunnelling, indicate that the ground movement into the tunnel was negligible. A plot of Inclinometer I-9A, which was located 4 m from the

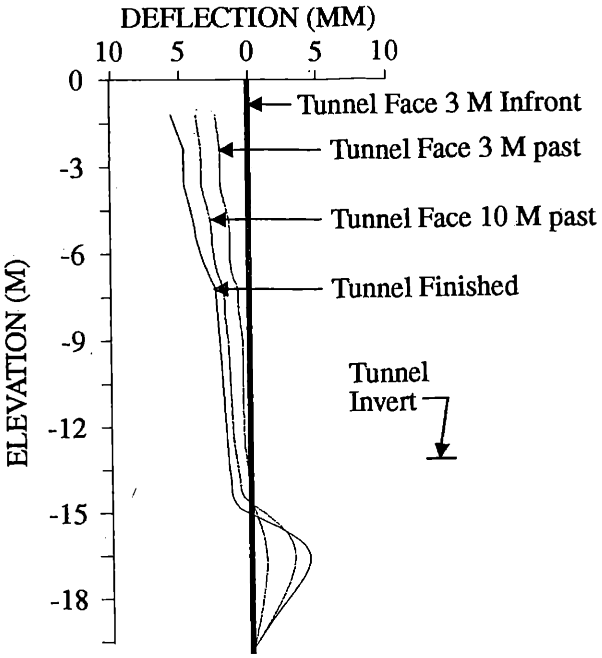

Figure 4: Plot of Inclinometer I-9A

center of the Undercrossing Tunnel is shown above as Figure 4. It is representative of inclinometer data obtained in the other inclinometers as well.

SUMMARY AND CONCLUSIONS

Jet Grouting was used to improve native soft clay to 12 times its in situ strength an eliminate squeezing ground conditions for construction of 232 m of 4.1 and 4.6 m diameter tunnels. One thousand 8 m long double fluid jet grout columns were installed from the ground surface to below tunnel invert in advance of tunnelling operations. The tunnels were excavated with an open face shield using a road header to cut and remove the grouted soils.

This method eliminated use of compress air and its associated risks, including loss of ground, health of workers, and fire. The overall performance of the jet grouted mass provided an initial ring of support which allowed installation of primary tunnel lining. It also facilitated excavation around and removal of numerous obstructions without impacting tunnel production.

During jet grouting operations ground heave, which occurred initially, was controlled. Overall movements at the ground surface during tunnelling were minimal.

This project was the first of its kind in the industry, and resulted in lower costs than originally estimated.