North American Tunneling'96, Ozdemir (ed.) © 1996 Balkema, Rotterdam. ISBN 90 5410 802 9

Jet grouted envelope for soft ground tunnel

Peter J. Nicholson
CEO P.J. Nicholson Consulting Co., McMurray, Pa., USA

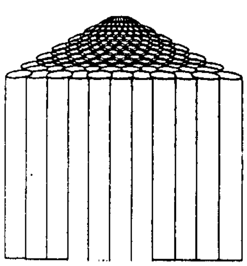
Donald A. Bruce
Nicholson Construction Company, Bridgeville, Pa., USA

ABSTRACT: As part of the City and County of San Francisco's upgrade of sewer facilities, a new storage/transport facility was required to be installed in the Islais Creek watershed area about 5 miles (8km) south of downtown San Francisco. The alignment required that the invert of the new tunnel be approximately 30 feet (9 m) below the mean low water elevation of San Francisco Bay, which lies about 1 mile (1.5km) north of the site. Compressed air and a compartmentalized breast boarding shield were specified by the owner as the means of construction. Kajima Construction and a joint venture of Nicholson/Rodio designed a value engineering proposal to jet grout, prior to tunneling, a cemented soil envelope in the Bay Mud that would totally encase the tunnel and 5 feet (1.5 m) outside the tunnel in hardened cemented soil. This cemented soil envelope allowed tunneling with road header, steel sets and wood lagging totally in dry conditions, without the need for compressed air.

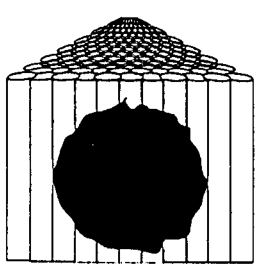
GENERAL BACKGROUND

Jet grouting to form a cemented pre-encasement for mining of a tunnel in soft silts and clays has been used in Singapore (Mongilardi 1986) in 1985. Other applications of jet grouting for tunnel crown protection by horizontal jet grouting have been numerous in Europe since the late 1980's (Bruce 1994). The introduction of jet grouting as a soil treatment technique in the United States began in the late 1980's where it was initially used as an underpinning method of protecting existing structures and frequently during adjacent open cut excavation activities.

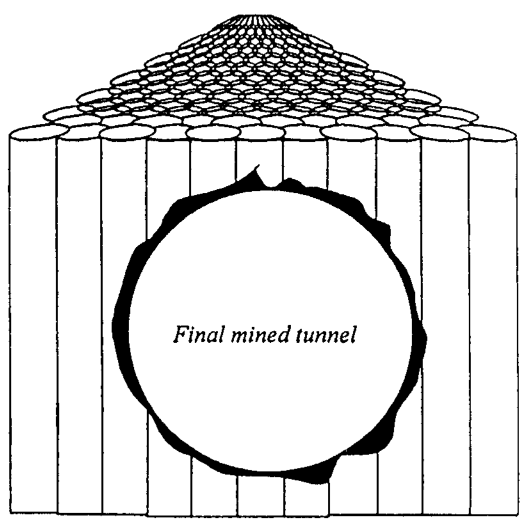
The first large scale use of jet grouting in the United States in fine grained, soft to stiff soils, occurred in Boston in 1994 as part of the Central



Overlapping columns of jet grout create cemented soil envelope.



Simple road headers, steel sets and wooden lagging are used to tunnel through the cemented soil in dry conditions.



Artery/Tunnel project. (Bruce, Pelligrino 1995 and Nicholson 1994). Here jet grouting was used as a pretreatment of the sub-grade for a deep excavation on the Bird Island Flats cut and cover tunnel adjacent to Boston's Logan International Airport. This $400 million project was a boat section tunnel approach to the new third harbor tunnel. It involved an anchored support of excavation wall, approximately 70 feet (21 m) deep, that was not able to resist a deep seated wedge failure in the clay. As a remedial measure, jet grouting and deep soil mixing were employed to increase the shear resistance of the clay and provide insitu buttresses for added wall support. Approximately 1500 jet grout columns, 5-6 feet (1.5-1.8 m) in diameter were employed with an average length of column of 35 feet (11 m).

ISLAIS CREEK BACKGROUND

As part of the upgrading of the combined sewer overflow storage, transport and treatment facilities of the City and County of San Francisco it was necessary to construct a 12 foot (3.6 m) diameter, steel lined tunnel in the Islais Creek drainage basin 5 miles (8 km) south of downtown San Francisco. The chosen alignment dictated a tunnel with an invert at an elevation approximately 45 feet (13.8 m) below mean sea level, that would tie into a pumping station at the eastern end of the tunnel. The path of the tunnel leads it directly under a dual track main line Tri-rail embankment and then parallel to and alongside an existing pile supported sewer. At the Rankin Street intersection, numerous other near surface utilities would be crossed, including a fibre-optic telephone cable (Figures 1 & 2).

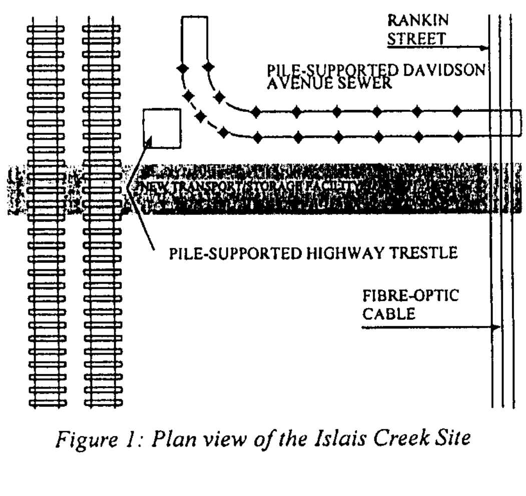


Figure 1: Plan view of the Islais Creek Site

Because of the existing structures, utilities and in particular the active commuter train line, the owner, and the engineer, Jacobs and Associates, were concerned about surface settlement and caving caused by squeezing of the tunnel face in the soft soils under the water table. The design called for a compartmentalized breast boarded shield, and back grouting to prevent subsidence in the tail void. All tunneling was to be under compressed air and the lining segments were to be fitted with gaskets to prevent inflow of water and loss of air pressure. (Edgerton,1995)

Kajima Construction, Pasadena California, who was the low bidder for the work at a price of $19 million, looked for an alternative to compressed air tunneling. They contacted Rodio Inc., the American subsidiary of Rodio S.P.A. of Milan Italy regarding the feasibility of jet grouting an envelope of cemented soil around the tunnel alignment prior to initiating tunneling. Rodio had successfully performed a similar project in Singapore in soft clays in 1985 (Mongilardi, 1986) and this method of pretreatment was becoming a more common means

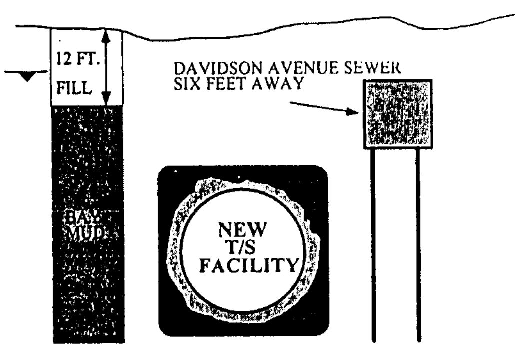
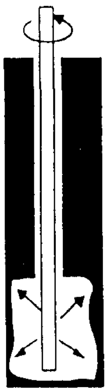


Figure 2: Sectional View of Site

of construction in the Far East. Rodio, in association with Nicholson Construction Co, Bridgeville, PA., submitted a value engineering proposal to design and construct a cemented soil envelope, approximately 25 foot (7.6 m) square, that would encase the entire tunnel to a distance of 5 feet (1.5 m) beyond the required neat tunnel excavation line (Figure 3).

After a test program that proved that the required treated soil strengths of a minimum 200 psi (1.4 MPa) could be achieved, the owner and engineer accepted the value engineering proposal. Jet-grouting work commenced in June, 1994 and was

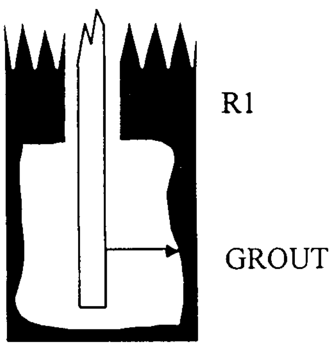


Jet grouting: General concept

completed in May, 1995. Tunneling began in March of 1995 and was completed in October 1995, using a road header and steel sets and wood lagging. The tunnel excavation was essentially dry, being performed in a soft concrete like material with a stand- up time that permitted easy placement of rings and lagging.

TEST PROGRAM

The design submitted by Nicholson/ Rodio envisioned a 25 foot (7.6 m) almost square cemented soil envelope encasement of the tunnel alignment. This size envelope would allow a minimum 5 foot (1.5 m) cemented soil overlap outside the neat tunnel excavation line in order to minimize water intrusion and provide stand up time. A minimum strength of the cemented soil of 200 psi (1.4 MPa) was selected in order to avoid the potential for squeezing of the soil at the open face of the tunnel excavation.

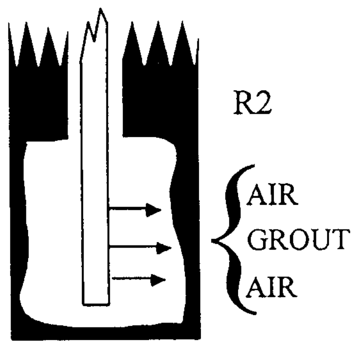


Jet grouting was developed in Japan and Europe in the 1970's (Bruce, 1994). It involves drilling a small diameter hole to the required depth, then introducing fluids into the special drill bit that are ejected horizontally through a special nozzle, at high velocity into the ground. There are three types of jet grouting commonly in use:

* A one phase system, designated R-l that involves a high pressure cement and water grout only.

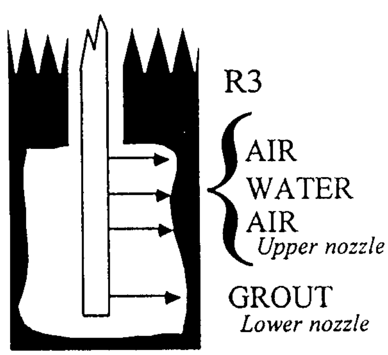
* A two phase system, designated R-2, that involves simultaneous injection of the cement grout encased in a shroud of compressed air. The compressed air allows the cement grout jet to do more extensive and effective cutting and mixing.

*A three phase system, designated R-3, that is the R-1 system with pre-cutting performed by an upper jet of high pressure water and air. With this system the water and air jet does most of the soil cutting and the cement jet is used mainly to replace the soil.



In all cases the fluid or fluids are injected while rotating the drill rods at slow speeds and simultaneously withdrawing the drill bit at a predetermined rate, in small increments. The fluid pressure and injection are controlled in such a manner that at the conclusion of the process the insitu soil and the cement slurry are uniformly mixed to form a cemented soil with a 28 day strength of between 100 (0.7) and 1000 psi (7 MPa).

For the Islais Creek project it was decided to test the use of the R-1 and R-2 type system. The R-2 system would be used for the majority of the work where the jet grouting could be performed using vertical holes. The R-1 system would be used where inclined holes were required in order to achieve complete coverage under the railroad tracks or other obstructing utilities. In addition to testing the diameter and strength of the columns, it was required that heave at the ground surface as well as lateral displacement during construction of the columns be closely



monitored and controlled.

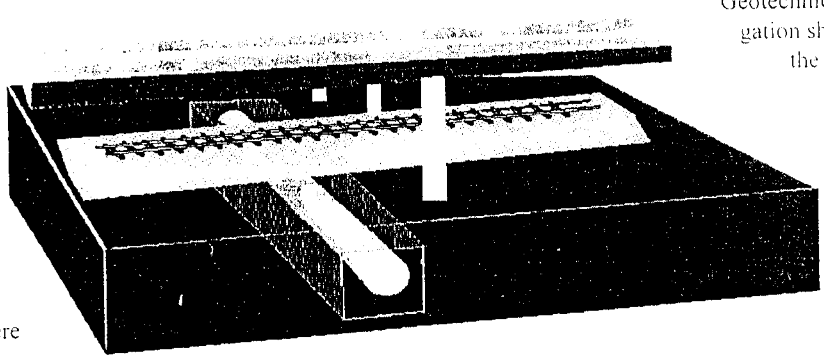
A total of 12 jet grouted test columns were installed, six R-1 and six R-2 to depths of 15 to 30 feet (5 m) below ground surface. The columns were installed using a variety of grout pressures, flow rates, target grout volumes and rod rotational speeds. Grab samples of the wet grout and soil mix were taken from each column during construction and were tested for strength at 7 and 28 days.

The exposure, examination and further testing of the test columns was accomplished by use of a braced sheet pile cofferdam. The R-1 columns were found to be circular with a diameter of between 2.5 and 3 feet (0.8-0.9 m). The R-2 columns were roughly circular with a diameter of between 6 and 7.5 feet (1.8-2.2 m). Cores and cut samples were taken from each of the columns and these revealed that internal consistency was uniform and homogeneous. The strength of both the grab samples and core samples gave results generally in the range of 200 to 500 psi (1.4-3.7 MPa), with only a few samples below 200 psi (1.4 MPa) at 28 days. Cores taken of the actual production work were typically over 500 psi (3.7 MPa) with some as high as 1000 psi (7 MPa). Heave and displacement were also monitored by the use of settlement gauges and inclinometers. At some monitoring points heave was greater than the allowable 0.25 inches (6.3 mm). This was due to the fact that in certain of the holes the annulus became plugged thus preventing the escape of the spoils. Since during the jet grouting process extra fluid volume is introduced into the ground, spoil must be ejected or displacement of the incompressible soil mass is inevitable. Sequencing of the work and changes in drilling and grouting processes were initiated that were able to control these heave and displacement problems and the test program was subsequently approved.

SITE CONDITIONS

Islais Creek lies on the shores of San Francisco Bay in a tidal marsh land that was reclaimed. The filling of the basin was hastened by using rubble from the 1906 earthquake. Subsequent filling with dune sand and other miscellaneous debris and rock fill left a ground surface roughly 12 to 15 feet (3.6-4.5 m) above mean sea level.

The fill overlies a sequence of young and old Bay Mud. Serpentine bed rock is at a depth of 80 to 160 feet (24-48 m) below ground surface. Geotechnical investigation showed that the horizon in which the tunnel was to be constructed consisted of soft to medium soft plastic silty clay or clayey silt generally classified as CH or MH. Shear strengths were generally in the range of 300 to 800 psf (15-40 KPa), and were classified as soft to medium soft. Consolidation is ongoing and therefore considerable movements are occurring, particularly under the 15 foot (4.5 m) high railroad embankment. The water table lies at about 8 feet (2.4 m) below ground surface and since dewatering would increase consolidation and accelerate surface settlement it was not permitted as a construction option.

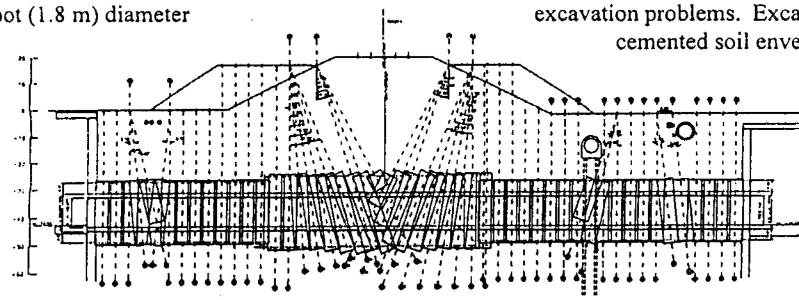


View of Interstate 280 ramp, Tri-County Rail and new T/S facility

In addition to the rubble and debris from the filling of the basin, there was a special concern about the railway embankment. It was known that an old railroad trestle lay buried beneath the existing tracks. The pile supported piers for the support of the I-280 viaduct were also close by. The Davidson Avenue sewer, which is also pile supported lay 6 feet (1.8 m) from the outside edge of the proposed soil cement envelope.

CONSTRUCTION

The main line of tunnel jet grouted was the portion adjacent to the existing Davidson Ave. Tunnel, a length of some 500 feet (150 m) at an average tunnel invert depth of 42 feet (13 m) below existing grade. The final inside diameter of the tunnel is 12 feet (3.6 m) with an outside diameter of neat line excavation of 15 feet (4.5 m). The tunnel portion of the railroad undercrossing was a lineal distance of 250 feet (75 m) at an average depth of 50 feet (15 m) below the railroad embankment. The final tunnel inside diameter here is 10.5 feet (3.2 m) and the planned excavation was 13.5 feet (4.15 m) in diameter. Based on the expected jet grouted column diameter a pattern of holes at 5 foot (1.5 m) center to center was established for the vertical R-2 columns. With the expected 6 foot (1.8 m) diameter columns this would give an overlap of 1 foot (30 cm), assuring continuity of the cemented soil envelope.



Angled jet grouting under rail embankment

Production drilling commenced in early July using a Casagrande C-8 drill rig with a special mast that allowed drilling in a single pass to the required 50 foot (15 m) depth. A bulk cement batch plant with a collodial mixer was set up along with a GeoAstra high pressure jet grout pump. A total of 600 columns were installed to an average depth of 48 feet (15 m) with a total jet grouted length of 14,000 feet (4300 m). At the eastern end, near the Rankin Street pump station, special protective measures against heave were instituted to protect the existing fiber optic telephone cable. Here extensive heave monitors were installed and the special precautions exercised ensured that heave was limited to less than 0.25 inches (6.3 mm).

The railroad undercrossing presented its own special difficulties. Here an embankment was required for a drill bench on both sides of the track so that angled drilling could be performed under the operating track. Layout of these holes and alignment of the drilling equipment had to be rigidly controlled in order to ensure complete encasement of the 25 foot (7.5 m) square envelope around the tunnel alignment. In addition, special controls were instituted on the drilling and grouting procedures to avoid heave and lateral displacement. In addition to the rail line, the I-280 piers were as close as 15 feet (4.5 m) to some of the jet grout columns; caution had to be exercised to avoid lateral displacements that could affect the piers or their steel bearing piles.

Production was started in July 1994 on the Davidson Avenue portion of the work and this was completed by October. Because of operating constraints, work on the undercrossing proceeded much more slowly, beginning in November 1994, and was not completed until May 1995. Excavation of the Davidson Avenue tunnel began in April and was completed in June 1995 at an average rate of 20 feet (5.1 m) per day. The speed of mining was controlled more by the rate of placement of steel set, lagging placement and spoil removal than by excavation problems. Excavation of the cemented soil envelope went without a hitch and, according to the tunneling superintendent, was like mining a soft concrete and after the first hundred feet he would have felt safe going the rest of the way "bald". There was only one quadrant of the tunnel for a length of some 15 feet (4.5 m) that showed any ravelling or signs of running water. The face stood vertical for long periods of time and there was essentially no pressure against the steel sets or lagging during the entire 6 month construction period.

Mining of the section under the railroad was ongoing as this paper is being written but as of October 1995 there were no reported difficulties and the entire work is scheduled to be completed in early 1996. During mining, there were no detectable or measurable surface movements and pumping of water was limited to 5-10 gallons per minute (0.3-0.6 /sec) for the entire 750 foot (230 m) tunnel.

CONCLUSIONS

A jet grouted cemented soil envelope was successfully installed prior to tunnel mining operations. It allowed elimination of compressed air tunneling in a soft Bay Mud. The cost of the jet grouting was offset by the reduced cost and increased speed with which the tunneling work proceeded. Surface settlement and disruption was minimized and the safety of the entire operation was enhanced by the positive support provided by the cemented envelope.

Even where surface obstructions such as railroad tracks precluded installation of the jet grouted columns directly over the tunnel lining, inclined hole drilling was employed. These inclined holes bypassed surface obstructions such as buildings or transportation structures that would otherwise limit immediate surface access to the tunnel alignment.

Heave and horizontal displacement caused by the jet grouting can be controlled in a manner that limits deflections or heave to less than 0.25 inches (6.3 mm). Water infiltration, face stability and surface settlement can be controlled to a much greater degree than with conventional breast board, earth pressure balance and compressed air tunneling methods.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Fred Dunham and Mr. Floyd Kerby of Kajima Construction Company and Mr. Guido Pelligrino of Rodio Inc. for their assistance in this project and paper.

REFERENCES

Bruce, D.A. (1994). Jet Grouting. Chapter 8 of "Ground Control and Improvement." by P.P. Xanthakos, L.W. Abramson and D.A. Bruce, John Wiley & Sons, Inc., New York, pp. 580-681.

Bruce, D.A. and Pellegrino G. (1995). "Jet Grouting for Solving Tunneling Problems in Soft Clays." Mexican Tunneling Conference, October 9-11, Mexico City.

Burke, J. (1995). "Success at Islais Creek." World Tunneling 8 (5) June, pp. N9-N14.

Edgerton, W., Berti, D.J., and Wong, M. M. (1995). "San Francisco CSO." Civil Engineering Magazine, May

Mongilardi, E. and Tornaghi R. (1986). "Construction of Large Underground Openings and Use of Grouts." Proc. Int. Conf. On Deep Foundation, Beijing, Sept., 19 pp. 68-71

Nicholson, P.J. and Chu, E.K. (1994). "Boston Central Artery Tunnel Excavation Support Remediation by Ground Treatment." ASCE Conf. On Soil Structure Interaction and Environmental Issues. Sept. 12-14