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Jet grouting for the solution of tunnelling problems in soft clays

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ABSTRACT: This paper describes the use of jet grouting in clays for two major tunneling projects in North America. The first example is for ground treatment associated with retaining wall remediation on a huge cut and cover section of the Central Artery in Boston. The second is for full face pretreatment, and structural underpinning, for a tunnel in San Francisco, where its use obviated the traditional need for compressed air.

1 BACKGROUND

Jet grouting is the youngest major category of ground treatment. According to Miki and Nakanishi (1984), the basic concept was propounded in Japan in 1965, but it is generally agreed that it is only since the late 1970s that the various derivatives of jet grouting have approached their full economic and operational potential to the extent that today it is arguably the fastest growing method of ground treatment worldwide.

Jet grouting can be executed in soils with a wide range of granulometries and permeabilities. Indeed, any limitations with regard to its applicability are imposed by other soil parameters (e.g., the shear strength of cohesive soils or the density of granular deposits) or by economic factors.

In contrast to the sensitivity and sophistication of some aspects of permeation grouting, the principle of jet grouting stands as a straightforward positive solution, using only cement-based grouts across the whole range of soil types. It therefore has the potential of being "designer-driven" as a technology, unlike the case with other grouting methods. However, it must be emphasized that any system that may involve the simultaneous injection of up to three fluids at operating pressures of up to 50 MPa must be handled with extreme care and only in appropriate applications, circumstances, and ground conditions.

Although applications have long been reported throughout the world, it is only in the last ten years or so that it has been used with any regularity in North America. Even then, most of the applications have been for structural underpinning or seepage cutoffs in granular soils. However, in the last two years, two significant applications have been conducted by the authors' companies for tunneling projects in soft, saturated clays.

While reflecting common practice, especially in the Far East, these applications are so far unique in the United States. This paper outlines these projects, with special attention paid to the reasons for selecting jet grouting, and the results of the process. The projects are:

- Contract CO7A1 in Boston, Massachusetts where jet grouting was used in excavation support remediation in a massive cut and cover tunnel, and
- Contract E, at Islais Creek, San Francisco, California, where full face pre-treatment of the clay permitted underground tunneling to proceed without the need for compressed air.

2 CONTRACT CO7A1, BOSTON

2.1 *Background*

The city of Boston, Massachusetts, is geographically constrained in its Central Business District by the Harbor to the East, and the Charles River to the North. Its main international airport is accessible only by a pair of tunnels that cross the Harbor. Tunnel portals are to the east of the existing North-South elevated I-93 (Central Artery). Massive traffic congestion in this area has led the Massachusetts

Highway Department to embark on an ambitious program which includes a new Third Harbor Tunnel (THT) and replacement of the existing Central Artery (I-93) with a cut and cover tunnel. This whole Central Artery/Tunnel projects is one of the largest highway and transit projects ever undertaken in the United States.

The East approach to the THT consists of parallel reinforced concrete box structures built in a cut and cover excavation. Excavation support walls using a steel beam-reinforced SMW (Soil Mixed Wall) method were selected to provide a ground water cutoff and a structural excavation support for the cut and cover excavation. Primary lateral support was by prestressed ground anchors. The SMW wall was made using overlapping 1 m diameter augers and mixing paddles that penetrate the ground at 610 mm centers while injecting a cement grout and mixing it with the soil. In total, about 40,000 sq. m of SMW shoring was created. The shoring included 3,700 tonnes of structural steel and 3,400 ground anchors of service loads 70-190 tonnes to stabilize excavations as deep as 25 m.

The general contractor for the 900 m long Contract CO7A1 was a Joint Venture of Modern Continental (Cambridge, MA) and Obayashi Corporation of Japan. The design-build subcontract for the excavation support was awarded to a joint venture of Nicholson Construction Company and SMW Seiko (Hayward, CA).

2.2 *Ground conditions*

The alignment passes through a complex set of ground conditions, due to distinct variations, both vertical and lateral, in the natural soils, and in the overlying fills. The area, known locally as Bird Island Flats was historically exposed only at low tide. A dredged shipping channel and various bulkhead walls were created. Successive stages of fills were placed to raise and level the site to its current elevation (4m NGVD).

For the purpose of excavation support, three successive distinct areas of the alignment were identified by the Area Geotechnical Consultant, from south to north:

- Zone A (330 m long): Sandy fill (5-6m) overlying 3 m of organics and marine deposits, underlain by dense glaciomarine deposits. These glaciomarines dominated the excavation face (maximum height 25 m).
- Zone B (280 m long): Variable deposits of sandy fill, cohesive fill, and man-made debris filling a 15 m deep, 180 m wide trapezoidal ship channel overlying very dense glaciomarine deposits at the approximate tunnel subgrade.
- Zone C (235 m long plus ramps): Cohesive and granular fills overlying organics, marine clay and glaciomarine. The soft marine clay (Boston Blue) is much thicker than elsewhere and the tunnel subgrade was to be founded predominantly on it. Typically it may have a shear strength over 70 KPa in its upper 5 m, but decreases to less than 50 KPa below. The water table was about 2 m below ground surface.

2.3 *The problem*

In Zone A, no significant problems were encountered during excavation, with wall movements upon completion being less than 0.2 percent of wall exposed height. Likewise in Zone B, despite the need to amend certain construction methods for the installation of the SMW wall in the ship channel, the final excavation performed well, and within the specifications.

However, for a 150 m long section in Zone C, the marine clay and organics were as much as 26 m deep. When excavation on a 60 m long section of the East Wall had reached the third row of anchors, about 13 m down, ongoing lateral movements of over 220 mm occurred over a period of time of about a month. Minor surface effects were noted 12-30 m back from this wall. Load monitoring of the anchors confirmed little or no loss of load, implying they were moving along with the entire soil mass, even though they were as long as 27 m. The excavation was locally backfilled and the movements ceased.

According to Cheney (1994), after intense studies, "the managing consultant concluded that the soil strengths shown in the contract documents were an upper bound value and probably not representative of conditions at the site of the wall movement."

Various remediation schemes were proposed to increase the shear strength of the clay, therefore providing resistance to the toe. The adopted scheme involved the formation of 1 m wide treated soil buttresses with clear separation of 1.5 m, in the base of the excavation over a length of about 250 m on each wall. Each buttress was widened near the wall to a 2 m wide "hammerhead." It proved most economical to generally create these by the (unreinforced) SMW method giving unconfined strengths of 2 MPa. These were keyed into the glaciomarine soils along the East Wall, but "floated" in the clay at the West Wall where geotechnical and structural conditions were better (figure 1). Details of the design are summarized by Cheney (1994). The large size and configuration of the SMW machine, and its ability to drill only vertically, meant that 2-3 m square gaps would exist between the wall and the buttress hammerheads. Jet grouting was therefore selected to provide these connections, install buttresses in restricted areas and also to underpin the base of the West Wall to minimize lateral or vertical movements during excavation and anchoring. This was the first example of large scale mass jet grouting treatment in clays in the United States.

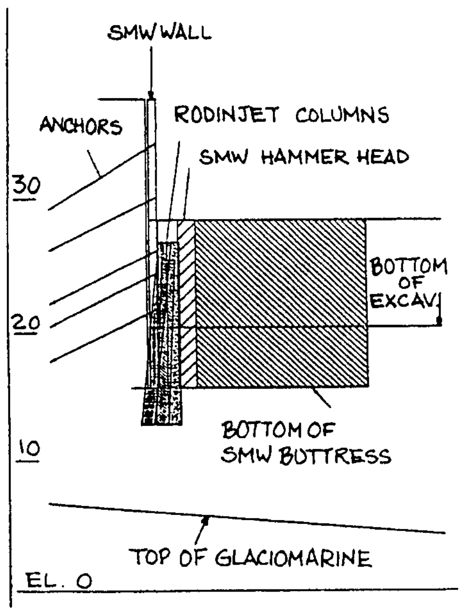

Fig. 1 Typical SMW-RJ buttress at West Wall, dimensions in meters (Nicholson and Chu, 1994)

2.4 *Jet grouting*

A design based on a conservative column diameter of 0.8 m, and minimum strength of 1.4 MPa at 28 days was prepared. This design featured six overlapping columns per hammerhead inclined at angles up to 8 degrees off vertical. A full scale field test was conducted to verify the actual insitu effects of the jet grouting.

On technical and economic grounds, the double fluid Rodinjet®2 method was selected for testing. Eight columns were installed in the clay near the East Wall. Each column was installed with a different combination of drilling and grouting parameters, with special attention paid to the potential benefits of pre-washing during drilling. Excavation exposure and coring of the columns followed. Columns of regular composition and shape, from 1.5 to 2.4 m in diameter were recorded, with strengths typically well over 2 MPa at 28 days.

Thereafter the production parameters and methods were determined including grout pressures of over 40 MPa, air pressures of 1 MPa, rod rotational speed of 10 rpm, and grout of water/cement ratio 0.8 (by weight). Production work then progressed. Special care was taken with the sequencing of column installation so that excessive volumes of the very sensitive clay would not be fluidized by jet grouting at the same time. A total of 14,500 lin. m. of jet grouting (in 1500 columns) was installed for the different purposes of buttress gap sealing and wall underpinning.

On the East Wall, small toe movements away from the excavation were recorded during hammerhead gap grouting. These were ascribed to the fact that the buttresses, being fixed in the competent glaciomarine, acted as immobile reaction blocks during grouting and so any volumetric expansion of the gap during grouting resulted in back movement of the (relatively flexible) wall.

2.5 *Performance*

Upon the conclusion of the SMW and Rodinjet® work, and after the treated soil was judged to have reached the target strength, carefully staged excavation and re-excavation progressed, with the introduction of additional ground anchors. Excavation was not at all hindered by the presence of the treated soil, which proved easy to remove and to dispose of (being a solid waste product). All wall movements have been within the owner's tolerable limits, and no excessive, sudden or ongoing deflections or settlements were recorded.

Prompt and decisive action by all the parties, acting in partnership, ensured that the unexpected extent of the problem posed by the deep and sensitive clay in Zone C has had a much less impact on project completion date than was at one point feared.

3. ISLAIS CREEK TUNNEL SAN FRANCISCO

3.1 *Background*

The Islais Creek Transport/Storage Project consists of upgrading the existing sewer system by construction of underground reinforced concrete box structures designed to store storm flows, and by connecting various existing sewer lines by new tunnels. The owner is the City and County of San Francisco Department of Public Works, and the general contractor is Kajima Engineering and Construction.

The two bored tunnel sections (used where the cut and cover method was precluded by the presence of existing structures) were originally foreseen to be mined through the very soft Bay Mud under compressed air. The temporary support was foreseen to be provided by bolted steel liner plates erected within the compartmentalized breast boarding shield, and back-grouted to prevent subsidence in the tail void. The lining segments were to be fitted with gaskets to prevent inflow of water, and losses of air pressure. The final lining, designed to withstand full earth pressure, was to consist of a steel pipe at least 32 mm thick.

3.2 *Ground conditions*

The project is within the Islais Creek basin, located on the south eastern side of the San Francisco urban area, north of the airport. Successive early survey maps show that most of the area was reclaimed from tidal marsh lands by filling with 8-12 m of dune sand, rock fill, miscellaneous debris and organic waste, resulting in a ground surface 3-6 m above mean sea level. The fill also often contains old piles, and even sunken ships.

The marine and continental deposits overlying Jurassic-Cretaceous bedrock include the Holecene Bay Mud (which controls most of the design and construction issues), Pleistocene Colma sands, and older clays, alluvium and colluvium. The Bay Mud is a plastic silty clay or clayey silt with variable amounts of organics, shells and sand. It is generally classified as CH or MH, and its consistency ranges from very soft to soft. It is easy to push the fingers of a hand into the in situ material which often has an undrained shear strength as low as 14 KPa. It ranges from normally consolidated to slightly over consolidated, with OCR values ranging from 1.05 to 1.62. Consolidation is ongoing and is therefore causing considerable movements: the maximum anticipated long term settlement below the Davidson Avenue Tunnel is about 0.25 m, related to a Mud thickness of about 30 m. At the railway embankment, the load itself is causing consolidation of the underlying Mud, resulting in an increased shear strength up to 50 KPa.

The water table is about 1.5 m below the surface, and since dewatering would result in general consolidation and accelerated surface settlement, it was not permitted as a construction option. The tunnel inverts were as much as 15 m below the water table.

3.3 *The jet grouting*

After the contract was awarded, a Cost Incentive Change Proposal was offered to pretreat the Bay Mud by Rodinjet and so eliminate the need for compressed air. A 2-D and 3-D F.E.M. analysis demonstrated that with a treated soil strength in excess of 0.8 MPa, conventional open face shield and road header could be used, together with wood lagging and steel ribs as temporary lining. The F.E.M. analysis also predicted settlements on the order of 10 mm.

A full scale test program was performed in order to demonstrate that:

- regularly shaped columns of certain minimum diameters could be created, thereby allowing the treatment of a continuous soil mass in the production works.
- the design minimum strength of 0.8 MPa could be achieved for the jet grouted soil.
- heave or settlement of surface and services could be controlled and minimized.

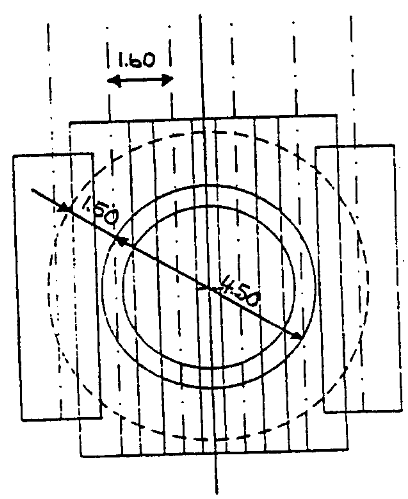

Fig. 2 Davidson Ave. Tunnel. Typical section and Rodinjet columns spacing (dimensions in meters).

A total of 12 jet grouted columns, six single fluid Rodinjet®1 and six Rodinjet®2, were installed in Bay Mud. Inclinometers and vertical-horizontal reference points were also installed before grouting began, to check the magnitude of ground movements associated with the jet grouting. Using a grout of water/cement ratio 0.83 (by weight), the columns were installed with a variety of grout pressures, flow rates, target volumes, and rod rotational speeds. Two grout samples were taken from each column for strength testing a 7 and 28 days. Results averaged 18 and 33 MPa respectively.

Excavation revealed R1 columns to be distinctly circular, ranging up to 0.9 m in diameter. R2 columns were similarly regular and ranged up to 2.5 m in diameter. Internal consistency appeared to be uniform and homogeneous. Cores and samples cut from the columns at various distances from their centers, showed R1 column strengths to average 3.4 MPa and R2 column strengths to average 1.4 MPa.. Subsequently, grout pressures of 40 MPa, air pressures of 0.8 MPa and rotational rates of 10 rpm were selected for the production work.

The Rodinjet®2 columns would be installed so as to completely treat the Bay Mud across the full face of each tunnel and for an annulus of about 1.5 m thickness all around (Figure 2). Most holes could be installed vertically, but surface conditions and a network of near surface services would often dictate the need for inclining holes. This was particularly necessary for the drive under the railway tracks (Figure 3).

The proposal covered the 4 m diameter drive approximately 80 m long crossing under Interstate 280 and Amtrak's main railroad tracks, and a 155 m long, 4.5 m diameter drive parallel to Davidson Avenue. This is the first example of full face tunnel pretreatment in soft soil in North America, although such practice is relatively common in the Far East (Mongilardi and Tornaghi, 1986).

About 900 columns were installed for a total of 6,800 m of Rodinjet®2 with drilling lengths up to 25 m. Special precautions had to be observed to limit movements, especially when treating under the railway where voids were likely in the fill as an old wooden railroad trestle was buried beneath the existing tracks. By the end of the jet grouting, none of the utilities or facilities that crossed or lay adjacent to the alignment suffered damage. In addition to the railroad and I-280, pile supported sewers, high voltage lines, a gas line, and telephone and fiber optic lines had all been encountered. Throughout, movements were very intensely monitored, and changes made to operational parameters to combat them. Control of movements is a critical feature of such work.

The success of the test program also encouraged the use of Rodinjet for other applications on the project. These included pre-support of sheet pile and caisson walls for open cut excavations, by grouting 2.4 m thick horizontal "kicker slabs" below the future cast invert slabs. These kicker slabs also reduced temporary bracing requirements. Rodinjet was also used as deep as 24 m to underpin existing structures which could have been impacted by the tunneling, such as major sewers along Davidson Avenue and at the railroad undercrossing.

3.4 *Performance*

Routine advances by open face shield and road header averaged 6 m per shift. Burke (1995) describes the ground as having similar excavation characteristics to the Marl encountered in the Channel Tunnel. Methodical testing on production columns showed unconfined compressive strengths

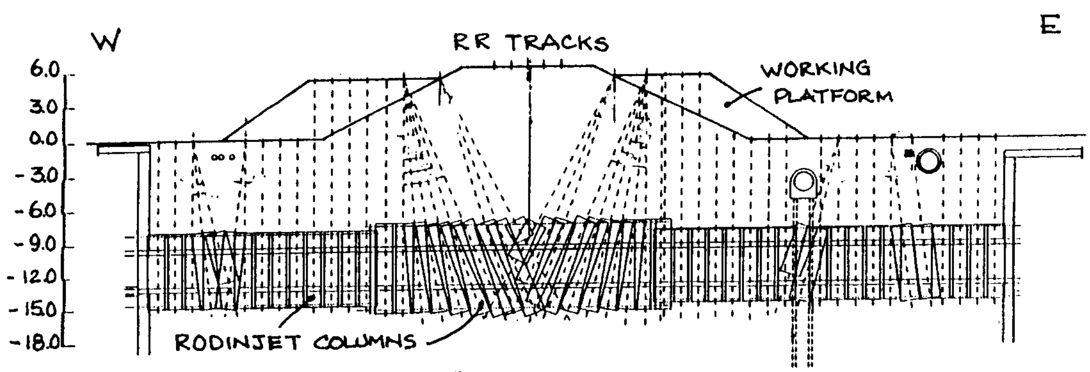

Fig. 3 Undercrossing Tunnel. Typical longitudinal section (depth in meters)

typically in excess of those recorded in the test program, with a maximum of 7.6 Mpa.

The tunnels were excavated virtually in dry conditions without ground squeezing. Surface settlements were negligible along the street and on the railroad tracks. The grouted ground proved uniform and competent and has, months after mining, shown no tendency to "collapse" against the temporary lining, even though the small annulus remains unfilled. The muck was hard, dry, and easily handled and disposed of. The system "has performed to everyones complete satisfaction" and has provided a fast, economical, trouble free, but above all, safe tunneling project in very difficult soil.

4 FINAL REMARKS

These two examples clearly illustrate the potential and performance of Rodinjet for the solution of tunneling problems in soft clays. Jet grouting has been used traditionally in North America for underpinning and seepage cut off in more granular soils: these case histories will hopefully be a source of interest and encouragement for geotechnical and tunneling engineers, faced with the need to engineer and excavate in less competent materials.

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., G. Pellegrino & A.D. Walker 1995. Ground Treatment for tunnelling: three new case histories. Proc. Tunnelling Association of Canada 13th Conf., Montreal Oct. 1995.

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

Cheney, R.E. 1994. Deep soil mix wall technology. Proc STGEL Conference Atlanta, October, 14 pp.

Miki, G. and W. Nakanishi, 1984. Technical progress of the jet grouting method and its newest type Proc. Int. Conf. In Situ Soil and Rock Reinforcement, Paris, Oct. 9-11, pp. 195-200

Mongilardi, E. and R. Tornaghi, 1986. Construction of large underground openings and use of grouts, Proc. Int. Conf. on Deep Foundation, Beijing, vol 2

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.