Geotechnical Aspects of Underground Construction in Soft Ground – Ng, Huang & Liu (eds)

Historical cases and use of horizontal jet grouting solutions with 360° distribution and frontal septum to consolidate very weak and saturated soils

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ABSTRACT: Horizontal jet grouting technology has proved to be quite a versatile tool for dealing with the particular geological conditions encountered when excavating tunnels in soil mass, especially in the presence of water flow and high hydraulic gradient. We describe the state-of-the-art application known as 360° distribution, in which horizontal jet grouting columns are executed around the excavated section, including the invert, and at the far end of the conical treatment, to create a watertight chamber. This results . in a heading that is constantly protected by pre-consolidated soil and minimizes the effects of excavation on nearby structures. We also describe a special tool (called the 'preventer') designed to control drilling and injection fluid outflow, which proved to be absolutely essential to successful outcomes. We also present the experience gained by the authors in a number of projects in Brazil and Venezuela and the results of a full scale test, executed for the first time in Europe.

1 INTRODUCTION

Horizontal jet grouting has proved to be an efficient and versatile technical solution and is increasingly being used for tunnelling in difficult soils, usually with high granulometry, presence of intense water flow and high hydraulic gradient.

Further developments have facilitated more non-TBM excavations in locations with low overburden and superstructure presence, such as urban areas where stable and safe conditions during excavation are required at all times, with minimum impact on nearby structures.

One type of application that is not yet in common use is the one in which horizontal jet grouting columns are executed all around the tunnel cavity in what is called a 360° distribution (roof, sidewalls and invert) and in which, depending on the circumstances, consolidation is extended to form a horizontal soil-cement frontal wall (septum) at the far end of the conical treatment.

Therefore, for the heading of the tunnel, a sequence of watertight chambers are created so that the excavation activity is always protected by pre-consolidated soil.

We provide a brief description of this innovative technical solution, its main geometrical characteristics and use conditions.

From the executive point of view, we describe the use of a special tool named the Preventer, which was developed to control the outflow of drilling and injection fluids, and is absolutely essential in order to obtain good performance.

Finally practical cases, executed by the authors, are described, along with the results of the first full scale test of a 360° jet grouting treatment executed in Europe.

2 360° DESIGN

In recent years, horizontal jet grouting technology has frequently been used for tunnels where safety was a priority and more traditional techniques were not feasible or might not guarantee good performance. As readers will know, this applies mainly to consolidating soil mass with poor geo-mechanical characteristics which do not allow excavation in safe conditions, mainly in sandy, silty or clayly soils or a combination of these, with or without presence of water.

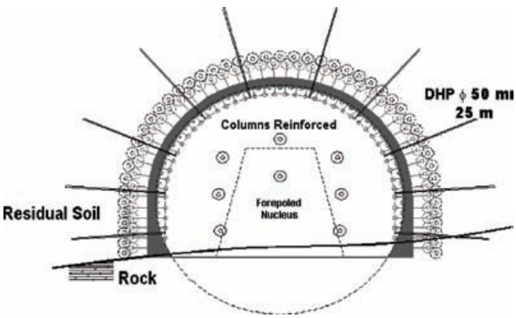

Figure 1. Typical distribution for roof and lateral protection and forepoled nucleus.

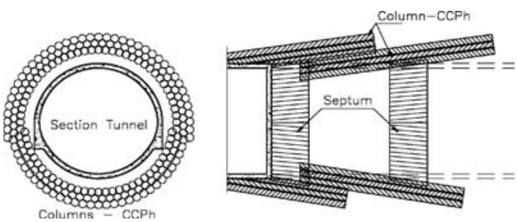

Figure 2. Typical distribution of a full face 360° distribution.

This technology is normally associated with the NATM . In a typical configuration, columns are executed side by side to form a pre-consolidated arch which follows the external profile of the excavated section.

Depending on the actual soil conditions, the consolidation effect may be improved by jet grouted columns executed inside the section to reinforce the tunnel's nucleus, or by means of horizontal drains drilled at the bottom or around the section. In more severe situations, the jet grouted columns may be reinforced by means of steel pipes or fiberglass, and drains may be equipped with vacuum systems. Fig. 1 shows a typical traditional distribution.

The encouraging results obtained from the horizontal jet grouting technique and the growing needs for executing tunnels in increasingly difficult conditions, at shallower depths, generally in alluvial or even residual deposits but with high granulometry, intense water flow, hydraulic gradient and the presence of important superstructures, as in many urban projects, prompted the development of the '360° distribution'.

The main characteristics of the 360° solution, compared to the traditional, are: a) soil consolidation, previously limited to roof and sidewalls, is now extended to the invert, and b) the execution of a jet grouted plug at the bottom of the conical treatment.

Thus a sealed chamber can be created, and in terms of stability, soil-mass loads around the cavity are redistributed to prevent possible inflows of material from the excavation face and the invert, which are quite common in sandy soils.

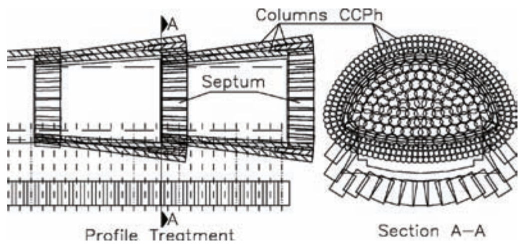

Figure 3. Example of 360° distribution for half-section and bench heading.

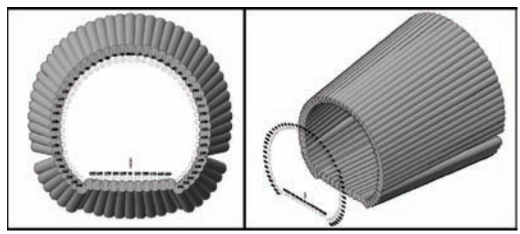

Figure 4. 3D Analysis of a 360° distribution.

From the hydraulic point of view, the drastic reduction of water inflow during the excavation phase reduces soil-mass dewatering and therefore keeps settlement under control and minimizes effects on nearby structures while the heading is executed. Fig. 2 shows a typical example of a 360 degrees distribution with full-face excavation.

Depending on the tunnel dimensions, the solution may also be adjusted for use with a half-section heading. In this case, the bench or final invert may be executed, if required by the geological conditions, with the help of vertical or inclined jet grouting to ensure safer conditions and optimize working schedule (fig.3).

As far as the operational aspect is concerned, the 360° solution became feasible due to advances in drilling equipment, involving redesign and improvement of its maneuverability, set up and mast alignment. Special homothetic templates with the projection of the consolidation elements for the perfect alignment of the drilling string had to be developed and implemented.

Also, 3D graphic tools were introduced in order to verify the integrity and continuity of the treatment designed (fig.4).

Special consideration must be given to the device used to control the outflow of drilling and injection fluids , which evolved from a similar one used in the oil industry, hence the name 'preventer'. Proper use of this device proved to be essential to achieve appropriate

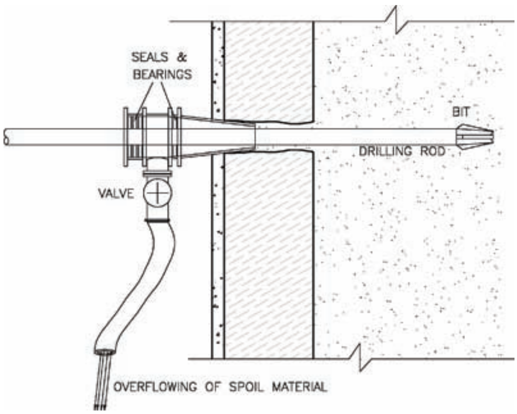

Figure 5. *Preventer* typical configuration.

Figure 6. Tunnel face with starting drilling points.

Figure 7. Septum and installation of yielding arch.

monitoring and control of movement of excavated soil mass.

3 THE *PREVENTER* CONTROL VALVE

The "preventer valve" (or "blow-up preventer") is used to avoid gas leaks and explosions when drilling oil wells.

Preventer valves and retainers at the mouth of the hole control outflows of solid and liquid spoils from drilling when ground is sandy and susceptible to "piping." They also facilitate control of slurry (excess soil-cement mixture) during jet grouting jobs, thus avoiding "piping" along the hole or the column.

Note that a drilling operation in non-cohesive soils below the water table produces withdrawal of material due to the intense flow established by the water table hydraulic gradient and water needed for the drilling operation itself.

In such case, it quite common to lose control of the volume of material flowing out of the hole if there is not proper perception of the phenomenon, thus triggering a piping effect.

This piping occurs when pressure inside the hole during the drilling operation is less than the effective hydrostatic pressure acting into the ground. And this can occur also during the jet grouting phase.

In this situation, with the *preventer* installed at the hole mouth, we may control pressure inside the hole, thus avoiding decompression of the surrounding material leading to an increase of permeability.

This device (fig.5) has a system of valves and seals to maintain strict control of volumes of materials withdrawn during drilling or injection. At the end of the jetting operation, it can also be sealed for the time needed for the soil-cement mixture to set.

4 HISTORICAL CASES

4.1 *Copacabana subway tunnel (Rio de Janeiro – Brazil)*

Rio de Janeiro's subway company planned a 750 m extension to line 1, from Cardinal Arcoverde Station to the center of Copacabana, also building Siqueira Campos Station and turn-offs or maneuvering areas. The underground structure comprised two independent but juxtaposed "eyeglass type" tunnels crossing gneissic rock, saprolite and micacious residual silty-sandy soil and sandy clayish soil of marine origin, of high hydrogeological complexity; the route also crossed a densely populated built-up area.

One of the greatest challenges was the NATM section of the tunnels under the direct foundations of a 50-year-old 7-storey building, standing on sandy sediment (beach sand), with around 6m overburden.

These tunnels were previously treated with horizontal jet grouting forming a closed 360° conical chamber with treatment throughout the excavation cross section and front septum protecting each advance module. (figs. 6, 7).

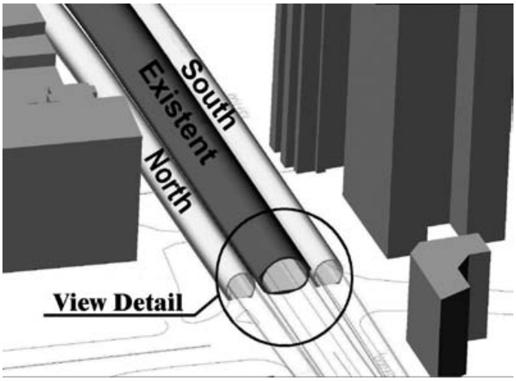

Figure 8. Plaza Italia/Capuchinos Twin Tunnels.

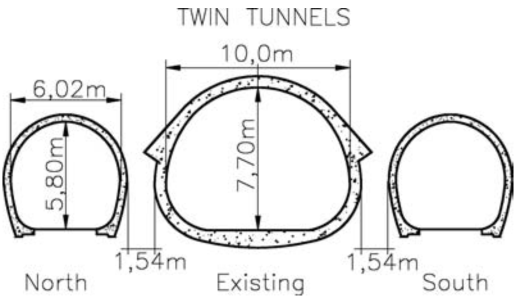

Figure 9. Section details.

The work was successfully concluded on time and the preventer valve was a crucial factor in ground treatment. The maximum settlement recorded was 30 mm.

4.2 *Plaza Italia Tunnel – Line 4 subway (Caracas – Venezuela)*

Part of the new Line 4, the North and South Tunnels Initial Sections, heading from Plaza Itália toward Capuchinos Station, involves the expansion of an existing station where two tunnels of approximately 6.5 m diameter were to be excavated on each side of an existing tunnel, which had to be maintained operational (fig. 8 and 9). In this case the existing structure, acted as a barrier to the ground water flow, raising its level and pressure.

On starting the excavation, instead of the residual soil predicted by the original geological investigation, tunnelers found highly permeable alluvial sandy soil with gravel at the bottom of the excavation section, topped by a claly layer of residual origin (micaceous schist), and a sedimentary fine sandy layer, at the upper part of the tunnel. The overburden was around 10 meters.

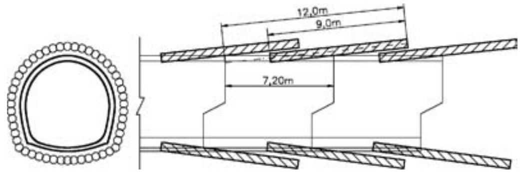

Figure 10. 360° horizontal jet grouting scheme.

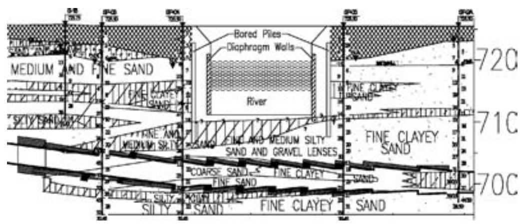

Figure 11. Geological profile and tunnel path details.

In order to cope with these difficulties, various preventive measures were taken in the design and execution phases. First of all, the design was adjusted to the in situ conditions, extending the vault treatment to the invert or locally, whenever it was necessary, so as to pre-consolidate and reduce water flow (360° Horizontal Jet Grouting, fig. 10).

Due to the presence of water under pressure, the drilling and jet grouting operations at the invert had to be executed using the *preventer* valve.

Since the central portion of the section proved to be in clay material, there was no need to execute a jet-grouted frontal septum.

However, specific measures to control pressure and water flow using deep horizontal drains, equipped with check valves when necessary, had to be taken.

4.3 *Tamanduatei river – service tunnel (São Paulo–Brazil)*

To our knowledge, this is the first case worldwide in which the 360° distribution has been adopted as a pre consolidation shape in a NATM tunnel.

In this case the challenge was the tunnel running at about 10 m under street level, but deepening to 25 m when crossing the river (Fig. 11) due to the project requirement for a minimum of 5 m under the bottom of the deepest diaphragm-walls containing the canalized river; this structure would pose a serious risk of becoming a preferential water-path communicating with the river bed.

The geological profiles (Fig. 11) showed that the tunnel is embedded in an alluvial mass deposited during the more recent Tertiary period. The matrix comprises coarse, medium and fine light-gray sands, with N(SPT) 10 to 40 and is very pervious at the tunnel's levels.

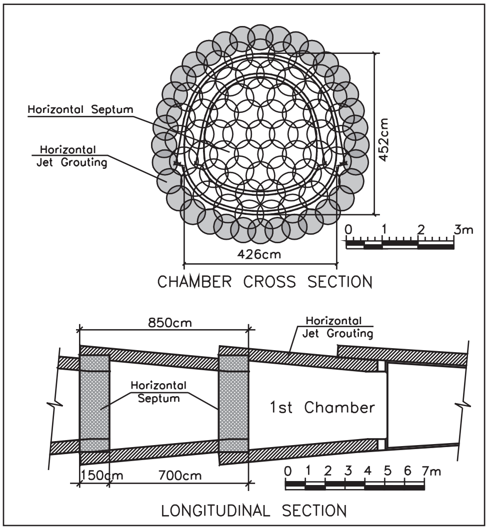

Figure 12. Treatment scheme with full section septum.

Inside this matrix, two highly plastic silty clay layers, 2 to 5 m thick, are intercalated but only randomly intersecting the tunnel excavation.

Water table observations showed a quick response during rainy periods. The same effect was produced whenever the level of the river rose due to rainfall anywhere along its upper course.

Before the excavation, as additional precaution, watertightness was checked by installing three horizontal drains inside the chamber so as to verify the presence of water under pressure and/or continuous flow.

4.4 *Full scale test for a railroad tunnel (Barcelona – Spain)*

The Madrid-Zaragoza-Barcelona-French Frontier high speed rail link's section connecting to Sants Station in Barcelona, required a tunnel with a 120 m^2 cross section located underneath the path of the existing ground level railway.

The geological investigation detected the presence of alluvial sandy material with high water table and high permeability, which was potentially dangerous for the tunnel's stability and the existing nearby structures, without special soil consolidation treatment.

In order to verify the efficiency of the horizontal or inclined jet grouting consolidation techniques in submerged conditions, it was decided to carry out a full scale test to confirm the feasibility of some alternative technical solutions proposed, verify the consolidation design parameters and check the effect of the activity at ground level, recording settlements and water table variations.

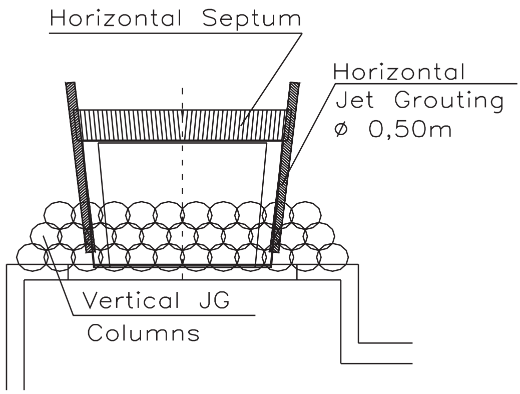

Figure 13. Full Scale Test – General lay-out.

Figure 14. Geological Profile related to the chamber position.

On a slightly smaller scale (80% of the original dimensions), the test reproduced the executive conditions of a consolidated horizontal half-section heading with all the structural and waterproof elements executed in accordance with the procedures and specifications stipulated for the actual structure.

Fig. 13 shows the general lay-out and geometry of the proposed treatment. The heading has been dimensioned to simulate the excavation of a stretch of tunnel 5 meters long between two jet grouted septums. The soil cover above the tunnel's crown is around 6 meters. Also the logistic and operational conditions facing the excavation crew during the actual work were accurately reproduced.

The geological profile at the test area is shown in fig.14. Basically it consists of a sequence of sandy to silty soils with SPT varying from 5 to 15, intercalated with very thin layers of silty clay. The presence of stiff gray clay was detected only well below the invert.

Between the tunnel's crown and invert levels, the soil is a very fine silt that is under hydraulic gradient and flowing out of the excavation almost without control. Since above the crown level there is no more

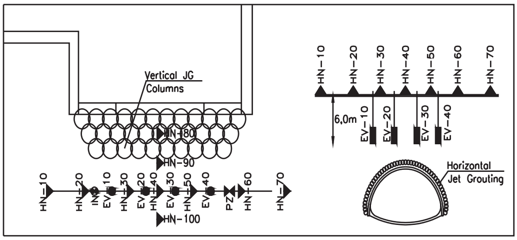

Figure 15. Instrumentation lay-out.

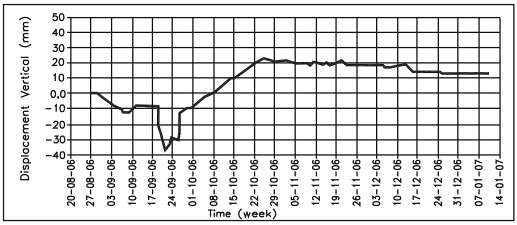

Figure 16. Bench Mark HN 40 – Readings.

consistent strata, even a small outflow is immediately reflected at the surface.

To verify the effects of the jet grouting injection onto nearby structures and the efficiency of the chamber's watertightness, piezometers and bench marks were installed, properly distributed above and around the test area (see fig. 15).

A number of horizontal drains with vacuum system were installed inside the excavation section in order to facilitate the chamber dewatering. A connection between the chamber and the soil mass outside would be detected by the external piezometers. The readings of settlements and water table levels were taken daily.

Fig. 16 and 17 show a summary of the data recorded throughout the test period. Despite very poor soil characteristics, it was possible to keep soil movements around the chamber and at ground level under control, with an average variation of about +/−20 mm.

The preventer (control valve system) was permanently installed except in a particular situation when, due to a technical problem with this device, a massive loss of material was experienced. Once the preventer was repaired, the original ground conditions were reinstated by injecting and recompressing the ground area affected. A pressure gauge was installed at the mouth of the device to verify the build-up of pressure inside the soil mass. A maximum value of 0.4 Mpa was recorded.

Piezometers readings were stable during the jet grouting consolidation phase. During the chamber excavation, one piezometer showed an anomaly indicating a possible gap in the consolidated area.

The problem was solved by reinforcing the consolidation with a small number of additional columns on

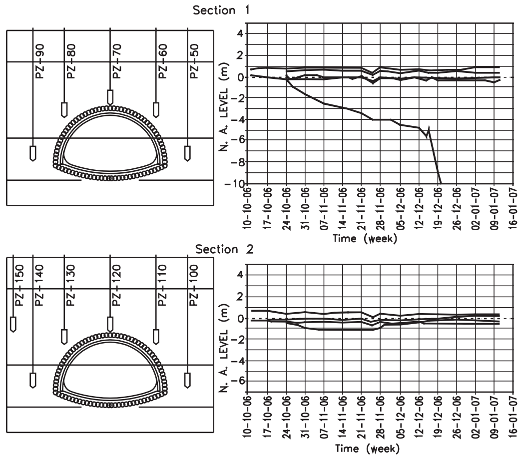

Figure 17. Piezometers Readings.

one side of the external alignment limited to the area affected by the phenomenon. The chamber excavation was successfully concluded confirming the stability and watertightness of the proposed treatment.

The test results were fully adopted in the design and subsequent execution of the main tunnel under the existing railway.

5 CONCLUSIONS

The 360° consolidation treatment is the state-of-the-art in terms of pre-consolidation technique associated with NATM mainly in alluvial or residual formations, with high granulometry and relevant presence of water pressure, and in general in all types of soil were jet grouting technique can form the column element.

To ensure the level of efficiency required, the instruments to pursue treatment's imperviousness and geometry are the *preventer* valve that is essential in order to avoid uncontrolled loss of material due to piping together with the special homothetic templates for perfect alignment of the drilling string.

The 360° consolidation scheme proved to be extremely flexible, as it can be adjusted to actual in situ geological conditions, and when executed in the appropriate manner and with proper equipment, achieves extremely good results in terms of ground movements, with a recorded average of 20 to 30 mm thus allowing a proper control of side effects on existing structures.

So far this technique has be implemented in urban tunnels with a minimum overburden of around 6 meters. The encouraging experience gained since 1998 when was executed for the first time, is at present leading the authors to study its application in even shallower tunnels with a soil cover of 3 to 4 meters.

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