Prototype tunnel in barcelona - test to check the construction feasibility with the 360º horizontal jet grouting and frontal septum

Prototype de tunnel à barcelone – test de viabilité de l´œuvre réalisée avec mortier d´injection horizontale à 360º et chicane frontale

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ABSTRACT

The authors are presenting here the behavior and instrumentation results of a prototype tunnel built to check the efficiency of a treatment fully carried out by horizontal jet grouting (HJG), applied for the first time in Barcelona, Spain. The 360° HJG treatment consolidates the unstable soil and stops the water flow all around the section to be excavated, including the inverted arch. It also creates a frontal septum inside the section, using HJG, so as to form a watertight chamber before the excavation. A specific site in the delta of the Llobregat river, composed by very fine, smooth and saturated sandy silt sediment (or vice-versa), was chosen to perform the test. It is typically a soil that can be washed away by the perforation water. The prototype tunnel presented a section equivalent to 80% of the section of the Madrid-Zaragoza-Barcelona-French Border High Speed Railway tunnel. After the test completion, the solution was accepted and its application to the main construction works found feasible.

RÉSUMÉ

Les auteurs présentent les résultats du comportement et instrumentation d´un prototype de tunnel pour la vérification de l´efficacité d´un traitement intégral de mortier d´injection horizontale ("horizontal jet grouting " - HJG), appliqué pour la première fois à Barcelone, en Espagne. Le traitement HJG à 360º consolide le terrain instable et étanche le débit d´eau autour de toute la section à excaver, y compris dans la section de l´arc inverti. Il engendre aussi, une chicane frontale, en HJG, à l´intérieur de la section afin de former une chambre étanche avant l´excavation. Un lieu spécifique fut choisi pour l´élaboration d´un test, de sédiment silt sableux, ou vice versa, très fin, meuble et saturé dans le delta du fleuve Llobregat. C´est un terrain typique qui émane conjointement à l´eau de perforation. Le prototype de tunnel représente une section équivalente à 80% de la section du Tunnel Ferroviaire à Grande Vitesse Madrid/Zaragoza/-Barcelone/Frontière Française. La solution a été acceptée à la fin de l´épreuve et son application viabilisée pour l´œuvre principale.

Key words: 360º Horizontal Jet Grouting and Frontal Septum, Preventer, Tunnel in Barcelona.

1 BACKGROUND

The urban section of the Madrid-Zaragoza-Barcelona-French Border , part of the High-Speed Railroad (AVE) Project, which links La Torrasa with Sants stations, in Barcelona (Spain), is located underneath the path of several railrways in operation. The tunnel, with a cross-section of approximately 120 m² and 1,500m long, has been designed with two construction methods: the first, known as the Belgian method, used on a length of approx. 900m, and the second, the New Austrian Tunnelling Method (NATM) for approx. 600 m.

In the NATM section, the tunnel had to cross sandy to gravelly alluvial soils, known as "paleo-valleys", with high permeability and high water table. The consolidation of the saturated sandy soil was necessary to keep under control possible unstable conditions at the crown as well as the invert of the tunnel, potentially dangerous for the nearby superstructures and tunnel safety.

As an alternative solution, the authors suggested to pre-consolidate the tunnel cavity, before the headin, using horizontal jet grouting (HJG) with a 360º distribution (roof, sidewalls and invert) and extending the horizontal consolidation to form a vertical frontal wall (septum) at the far end of the conical treatment. In doing so the heading of the tunnel would always be protected by a sequence of preconsolidated soil watertight chambers.

To check the efficiency of such solution, the contractor decided to carry out a full scale test in an separated area. Due to the importance of the investigation results, the test was well instrumented with surface marks, tassometrs and piezometers and with the technical supervision of the Polytechnic University of Catalonia (UPC), Barcelona

The application of a special tool, called "preventer" designed to control the outflow of drilling and injection fluids, turned out to be fundamental to the test success and the technical solution acceptance, as it was experienced in many previous projects. (Guatteri et al. 2000 and 2008).

2 HORIZONTAL JET GROUTING TREATMENT (HJG)

The first experience using HJG in Brazil was carried out in a Campinas (SP) highway tunnel (1988), while the first 360º HJG with frontal septum has been carried our in a tunnel under the Tamanduateí river (SP), (1998). The HJG technology has been increasingly used in Brazilian urban tunnels, and since 1988, the authors had gathered experience executing in the execution of more than 1 million meters of Horizontal Jet Grouting (Guatteri et al. 2008). The main characteristics of the 360° HJG solution are:

a) soil consolidation to form of a continuous pre-coating around the tunnel cavity extended to the invert, thus sealing the entire section. The column diameter is generally around 0.50m.

b) execution of the frontal septum with HJG columns at the end of the conic chamber formed by the 360º process. The column diameter generally is of about 0.80m.

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The continuous jetgrouted coat around the cavity helps to redistribute the loads originated by the excavation and avoids the inflow of material (Guatteri et al. 2008) providing stability to the heading. The dramatic water flow reduction during the excavation phase diminishes the effects of the water table drawdown and soil decompression, keeping settlements under control and minimizing the effects on the superstructures.

As far as the operational aspect is concerned, the application of the 360° HJG solution is possible due to the improved maneuverability of the drilling rig (positioner), set up and alignment which allow to execute the jet grouted columns practically in any direction, including under the working platform. Special homothetic templates with the projection of the consolidated elements and use of laser beams for a perfect alignment of the drilling string were developed. Also 3D graphic tools were introduced in order to check the continuity of the designed treatment.

3 THE PREVENTER CONTROL VALVE

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

A drilling operation carried out in non-cohesive soil under the water table produces the withdrawal of material due to the water table hydraulic gradient and flow of water needed for drilling operation itself.

In such conditions, it is common to lose control of the volume of material flowing out of the borehole, triggering the phenomenon of “piping”.

The “preventer” is a special device placed at the mouth of the hole by which we may control the outflow of material and the pressure inside the hole, avoiding decompression of the surrounding materials which cause increase of permeability and loss of strength of the soil mass (Guatteri et al. 2000 and 2008).

This device 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 GEOLOGICAL ASPECTS OF THE TEST AREA

The area chosen for the test is located on the Llobregat river delta, outskirts of Barcelona, and is characterized by geotechnical properties much poorer than the construction site.

The test area presents a 30 m thick sedimentation strata of fine, non-cohesive and saturated soils, mainly silt with transitions to a very fine sand and vice-versa.

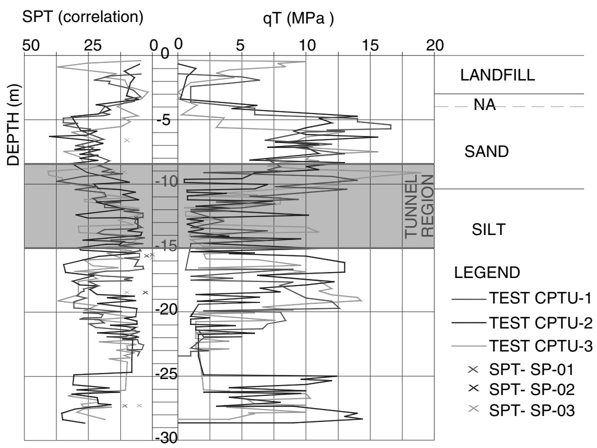

Fig.1 - Simplified geotechnical profile

The simplified profile (Fig.1) in the tunnel region presents the following sequence:

– At the tunnel crown, a non-cohesive soil layer with very fine sand and some random erratic lenses of gray silt with a variable thickness of 5 to 7m, average CPT values of about 8 MPa and SPT values 15 to 25. The water level has been found at 4 m in depth, at the top of this layer.

Fig.2 – Coring sample from 13.2 to 16.5 m

– For the lower part of the tunnel section, a sequence of silty soil and very fine gray (Fig. 2) sand depositions predominates, with CPT value ranging from 1 to 4 MPa, average of 2 MPa, and SPT value from 1 to 6.

– Below the invert the alluvial sediment showed to be more resistant, with an average CPT value of about 6 MPa (the most sandy layer) and of 2.5 MPa (silty layer), respectively.

5 TRIAL TEST DESCRIPTION

In order to simulate conditions more severe than those of the AVE tunnel site, with low overburden and high water table, a special trial field was constructed with an 18 m wide and 17 m deep square well and a 90 m long, 5 m wide access ramp. The side containment was performed with 1.0 m thick diaphragm wall duly reinforced with metallic beams.

The soil behind the diaphgram wall, in correpondence to the tunnel section, was reinforced by means of Ø1.8 m Vertical Jet Grouting columns (Fig. 3). The consolidated block (17m x 10 m x 3.2 m) was foreseen to allow the demolition of the diaphragm wall within the tunnel section and, at the same time, to accelerate the drilling operations.

The proposed consolidation treatment was formed by a double line of Ø 0.50 m HJG columns, distributed around the entire excavated section (roof, sidewalls and invert) characterizing a 360° consolidation, completed with 3.0 thick frontal septum at the end of the conical treatment, with Ø 0.80m columns.

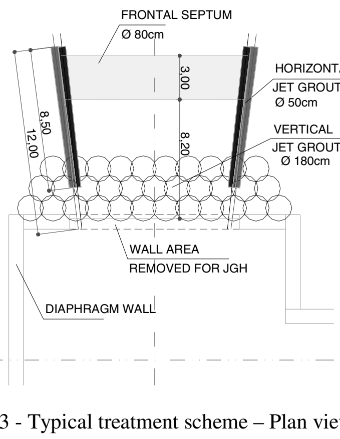

Fig. 3 - Typical treatment scheme – Plan view

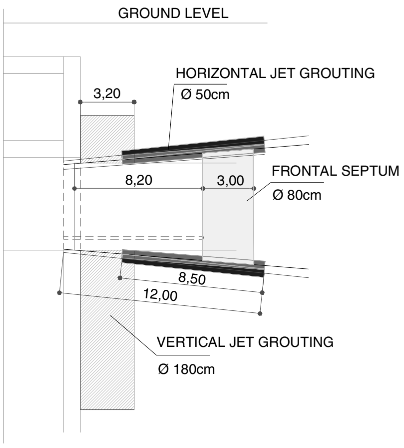

Fig. 4 - Typical treatment scheme – section view

The conical treatement was dimensioned to simulate a 8.2 m heading, with 5m between the JGV vertical septum and the HJG septum, (Figs. 3 and 4). The HJG execution parameters for columns used during the test, are summarized in Table 1.

Table 1 - Summary of Horizontal Jet Grouting parameters

HJG	w/c	Pressure (MPa)	Flow l/min	RodSpeed m/min	RodRot. rpm
Ø 0.50	1:1	35	80	37	13
Ø 0.80	1.2:1	40	110	34	14

The trial field was instrumented (HN) with ten superficial marks (HN) and 4 tassometers (EV). The chamber watertighness was checked by means of a network of piezometers (PZ) installed around the tunnel section, placed externally to the treatment right after its execution.

Eleven tube piezometers were installed along two sections, one close to the vertical septum contact with the HJG, another at the contact between HJG and the frontal septum. An additional piezometer was installed behind the frontal HJG septum along the tunnel axis (Figs. 5 and 6).

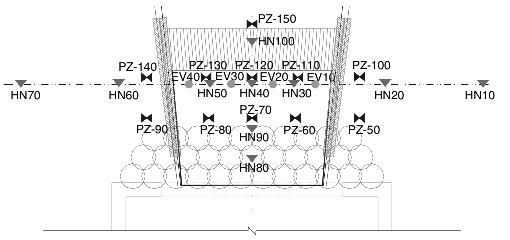

Fig. 5 - Instrumentation set up – Plan view

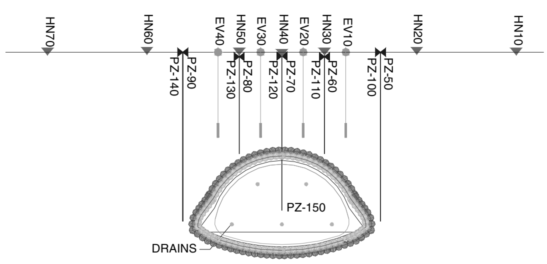

Fig. 6 - Instrumentation set up – Section view

At the beginning, it was very difficult to control the volume of material flowing out of the borehole, as the silt and silty sands showed to be very fluid, almost like water, causing piping effect during both drilling and jet grouting operations.

Many peculiar executive aspects were faced during the test, and necessary adjustments to the proposed procedures had to be introduced. In particular:

a) The outflow regulating valve (*preventer*) had to be kept installed all the time in order to control the flow of material at the hole mouth, during drilling and injection phase. Furthermore, the same device had to be mantained in position, sealed, for a period of up to 40 minutes after the completion of the column until de soil cement had started to cure. After that it was replaced by a wooden plug (Figs. 7 and 8).

Fig. 7 - Positioner carrying out HJG at the invert

b) The preventer had to be equipped with a pressure gauge installed at the outlet control valve, in order to measure the pressures induced into the soil mass. Throughout the work, the average pressure recorded was around 0.4 to 0.6 MPa.

c) As consequence of the soil instability, the whole central section of the conical chamber, to be excavated at later stage, had to be consolidated with horizontal jet grouting columns. This decision was taken in order to avoid that the uncontrolled outflow of material during the excavation could jeopardize the pre-consolidated arch stability and the safety of the excavation team safety. UPC suggested, for testing purposes, that soil treatment inside the chamber should be carried out also with low pressure injections. The tunnel section was divided in four areas, where four different types of consolidation would be executed: horizontal jet grouting, silicate injection, micro-cement and regular cement injection. For each test, the same drilling grid used for the injection of the frontal HJG septum should be applied. However the conventional injection was not successful, and the whole area had to be consolidated with HJG.

Fig. 8 - Test tunnel under excavation

d) Fig. 9 shows the most representative data from the instrument readings during the test. It is to be noted that, despite the strong tendency to soil liquefaction, it was possible to keep the soil mass movements restricted to the treated section and at the surface, and in a reduced range varying + / - 20 mm, recorded during the septum columns building phase.

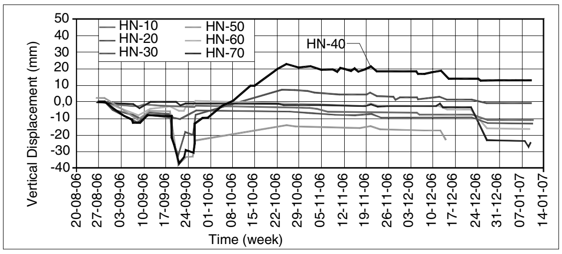

Fig. 9 - Superficial marks - HN 40 highlighted

e) The preventer's efficiency to control settlments or upheavals was confirmed, allowing, when needed, also the "recompression" of the overburden. That event was confirmed in a particular situation, when, due to a serious damage, the preventer had to be replaced while the drilling operation was ongoing. As consequence an uncontrolled discharge of approximately 8 m³ of water and solids occurred, in a very short time, until the device could be replaced. The instrumentation recorded an immediate settlement of approximately 40 mm (fig. 9). Despite the loss of volume, it was possible, using the preventer, to carry out the soil mass recompression, thus reestablishing the original terrain level.

f) As preliminary control carried out before the excavation, horizontal vacuum drains were installed. The piezometer readings recorded very little changes, except for one piezometer (PZ90), which showed a possible communication between the inner chamber and the exterior, at a left side area (Fig. 10). The problem was solved by installing a series of additional columns in the region affected by the phenomenon.

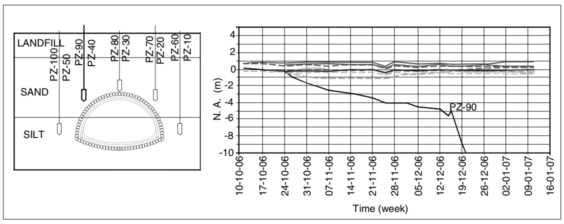

Fig. 10 - Piezometric readings - see PZ 90

g) The excavation of the test section was completed in perfect safety, confirming the treatment's watertightness (Fig. 8), and the proposed solution, added to the available technology and the experience of the companies involved, resulted reliable for adoption in the main construction.

6 FINAL COMMENTS

Only the execution of a prototype tunnel test, with the characteristics of an actual construction, could gather the necessary information that would allow the entities involved, client, designer and builder, to incorporate the concepts of the solution proposed by the authors for the construction of the urban section of the High Speed Train, Madrid-Zaragoza-Barcelona-French Border , in Barcelona, Spain.

The challenge to cross several sandy and saturated "paleo-valleys", with low overburden and underneath already implemented superstructures was faced by means of an alternative solution using Horizontal Jet Grouting technique, with watertight chamber formed only by horizontal jet grouting (HJG) columns placed in a 360º distribution and with a frontal septum at the final end of the conical section.

The proposed solution was applied for the first time in Europe, although it was already succesfully used in several tunnels in Brazil and Venezuela, since 1998.

The succesful excavation of the prototype tunnel showed that, compared with different injection technologies, the combination of horizontal jet grouting and 360º distribution was efficient to overcome the expected difficult soil conditions.

After the trial test, the feasibility of this solution in the main construction was confirmed, under a full technologic control. The main construction was built with absolute success and the Madrid - Barcelona High-Speed trains are already in operation.

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