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ABSTRACT

EOLE is the line E of the Paris express subway network serving two new stations: Magenta and Haussmann, located in the capital's most important business districts. The project is designed to provide relief to the current network which had reached saturation in the East-West direction where the public resides in the East and work in the West. With its subterraneous network of connections and passageways, EOLE is a vast underground complex, a place of constant exchange with the urban environment, set in the very heart of Paris.

Conquering the underground, supporting the city, domesticating space, architectonising concrete, bringing light under control, integrating the project into the city, minimizing the impact of construction work on living environment of Parisians, etc., such were the engineers and architects challenges in building the EOLE unprecedented stations. In this paper, the design and construction details of the project NATM stations are presented in detail.

INTRODUCTION

EOLE is a latest line of the RER (Regional Express Network) in Paris linking eastern and western suburbs via a 4 km underground track serving two new stations located in the capital's most important business districts. These stations provide numerous connections to the subway, buses and mainline train stations, and also allow access to two major Paris department stores. The construction of these large stations in the Parisian underground was one of the major challenges of EOLE project; it was the question of building the largest cavities ever built in these grounds, without creating unacceptable deformation or distress to the surface buildings.

The urban section of the project almost entirely underground was one of the biggest construction jobs in the region and undoubtedly one of the most technically complex. The growing congestion of the Parisian underground and its geology required the planners of the EOLE project to consider a deep underground infrastructure. The existence of these stations, with exceptional dimensions and with a strong architectural component resulted in considering EOLE as a vast underground complex. In addition to a dense and decaying built environment, the Parisian site is saturated by a grid of networks and obstacles which influence the urban life. Thereby, EOLE was excavated in this tightened entanglement and crossed heterogeneous geological layers.

Surrounded by mid 19^{th} and early 20^{th} century buildings, the stations are true underground cathedrals, 225 m long, 60 m wide (central vault span of 20 m) and 15 m high, with an average crown depth of 20 m constructed in difficult geological condition and under water table below old and heavily built-up areas totally devoid of free public space. All links to the surface; passenger access and circulations, ventilation shafts and emergency exits had to be integrated into private urban domain. The EOLE project is at the very intersection of the railway tunnels and the city itself. The architects, engineers and contractors were passionately involved in the management of this complexity.

Several feasible architectural designs were studied and compared:

• a structure with single vault and two levels

• a double vault structure

• a triple vault structure comprising a large central vault and two side vaults. This solution presented two alternatives: one with a mezzanine under the central vault, the other with intermediate abutments between central vault and side vaults.

Several methods were considered for the construction of these scenarios: pillar and room method, cellular arc technique, method of presupport by forepoling or joined galleries, divided section method, etc … Indeed, the evaluation of surface settlement by finite element analysis showed that the triple vault solution with intermediate abutments presented the optimum option.

Construction work started at the end of 1993 and finished in mid 1999. The construction method adopted the traditional principles of underground work in Paris in the beginning of the 20^{th} century (with wooden temporary support at the time): first construction of the sidewalls, then the roof and finally the invert. The size of openings was always limited so that smooth stress redistribution is observed. A typical section of the station consists of the main central tunnel and two side tunnels: the west and east side tunnels. The roof of the central tunnel is an active vault of concrete segments prestressed against surrounding soil to reduce stress relaxation. This active vault is supported by sidewalls constructed during the excavation of the side tunnels (Figure 1).

The primary concern for the engineers and contractors was the control of surface subsidence, which dictated both the construction methods and the geometry design of the stations. The initial and final liners were designed to ensure minimum impact on the environment at every single stage of construction and the best possible conditions for the buildings to resist the long term effects. At the outset of initial feasibility studies, mathematical modeling was used to compare different methods and structures, and to analyze the effectiveness of various soil improvement techniques.

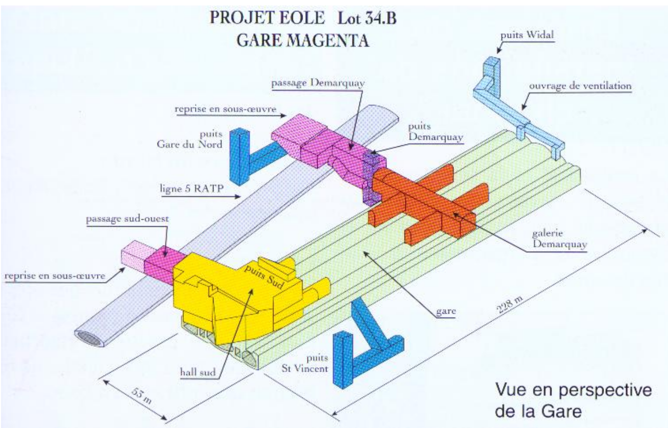

Fig. 1: 3D view of the Magenta station

GEOLOGICAL CONTEXT

One of the difficulties of the project was control of the deformations in the ground due to excavation work and their detrimental consequences on the surface even though the layers to be crossed were known because of many underground works undertaken since the beginning of the century. The soil profile is typical of the sedimentary soils in the Paris region:

• 3 to 5 m thick recent fill composed of silty gravel, black organic silt and coarse sand strata
• gypseferous soft marl including dissolution cavities or sinkholes filled with alluviums or quaternary deposits (5 to 10 m thick)
• green sand (0.5 m thick)
• Saint-Ouen limestone composed of alternate layers of marl and limestone (including gypsum 14 to 16 m thick)
• Beauchamp sand, fine to clayey very dense sand (10 to 14.5 m thick)
• alternate layers of white marl and silicified or shelly limestone and gypsum with dissolution features (Figure 2).

The phreatic surface is composed of two aquifers: one within the recent fill and the other within the Beauchamp sand.

Boring and sampling were carried out, to which were associated laboratory tests (identification, mechanical tests) or in situ tests (pressuremeter, delayed logging). This work was, of course, accompanied by piezometric readings to differentiate the various water tables and to determine their characteristics.

A major difficulty was related to the presence of gypsum in the North-East of Paris where the project was located. Indeed, many of gypsum quarries, generally exploited in the open air, were backfilled and today this fill supports the foundations of dense and decayed buildings. In addition, it is known that the variation of ground water level causes the dissolution of gypsum lenses, thus creating voids with volume reaching several thousands cubic meters. This epiphenomenon of dissolution weakened Beauchamp sand and created sensitive geological zones, recognized by the geophysics investigations based on the microgravimetry and seismic.

To complement this investigation, several more targeted operations were undertaken:

• excavation of three shafts and exploratory tunnels intended to observe the ground and to measure their in situ characteristics

• pumping tests in the stations zones in order to model the aquifers of these zones

• jet grouting and grouting tests in the stations areas.

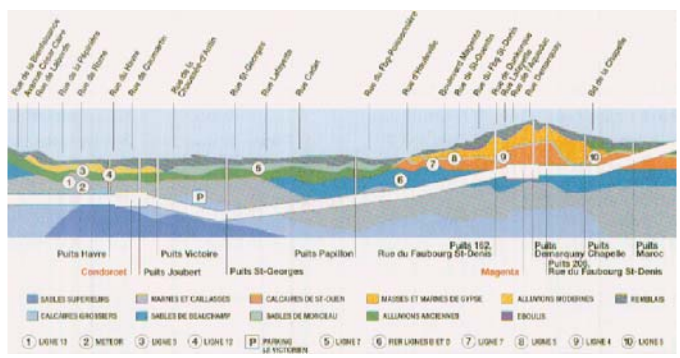

Fig. 2. Geological Profile

ARCHITECTURE OF THE STATION

The adopted solution, with no mezzanine, was explored by the architects who placed great effort in emphasizing the harmony of the vaults and representing diffusion of the forces through the hollow abutments by various shapes and texture of the finishes. The selected design gives an opportunity to the commuter to admire the vault while waiting for the train (Figure 3). For the upper concourses, a structural system of struts and posts was arranged judiciously to release large volumes lightened by natural light, and to open broad views to people reaching the structure (Figure 4).

Fig. 3: Completed central tunnel

It was not the first time that a project of the RER line planned large underground stations in Paris, but it was perhaps the first time that the design of such stations, before being technical, was architectural. In previous cases, the architect intervened relatively late, while the principal volumes were already defined in order to strictly meet the program needs. He was coming to somehow add architectural ideas to the work of engineer. In the case of EOLE, it was completely different since the architect intervened early, proposing from the beginning generous volumes meeting not only the strict program needs, but also offering a clear legibility of spaces and a comfortable environment providing a feeling of safety for the commuter. This concept of legibility implies spaces of a certain size, rarely compatible with construction in underground.

Fig. 4: Finished concourse

The architecture of these stations, a result of the inherent constraints of the project (depth, congestion of the underground, limited right of way on the surface) was very specific and required adapted technical solutions in view of expected high flows of commuters and their management in necessarily restricted spaces.

The EOLE stations are significant architectural success in making it easy for passengers to find their way around with visual continuity and carefully designed connections between the different areas, optimizing orientation and reducing distances to minimum, avoiding the impression of confinement and providing passengers with the best possible comfort. Particular attention was paid to decorative and surface materials and to the way in which surface areas were used. The materials employed were luxurious: metal (copper, aluminum …), exotic wood, concrete with multiple finishes (white, satin, shiny …), marble ….

SEQUENCE OF CONSTRUCTION

The defined elevation of the stations was the result of a difficult compromise between operational and technical constraints. Indeed:

• the stations could not have been too deep so as to reduce passenger egress times and to allow a favorable energetic alignment profile

• they had to be sufficiently deep so that the vaults benefit from the presence of the stiffer layers.

The height of these stations prohibited them from being entirely in the same layer of ground. So, if the vaults could be placed in rather favorable levels, the abutments and inverts were located in water bearing sands particularly sensitive to excavation.

A basic decision led to the construction of the station in two stages. The first stage included half of the top heading of three of four longitudinal galleries required for the construction of the underground station abutment and allowing important geotechnical and geophysical analyses for the second stage.

The second stage was extremely delicate since the structures were dependent on each other and the work had to progress on all faces to remain within the contractual schedule (Figure 5).

The complexity of the structures required significant studies, using finite element method within the framework of a sensitivity analysis by varying the deconfinement coefficient.

With regard to the dissolution of gypsum, calculations were performed to design the structure with the assumption of a 4 × 4 m void at the most unfavorable location.

For the underground station, the ground water table elevation considered for the hydrostatic pressure analysis was assumed to be located above the platform level.

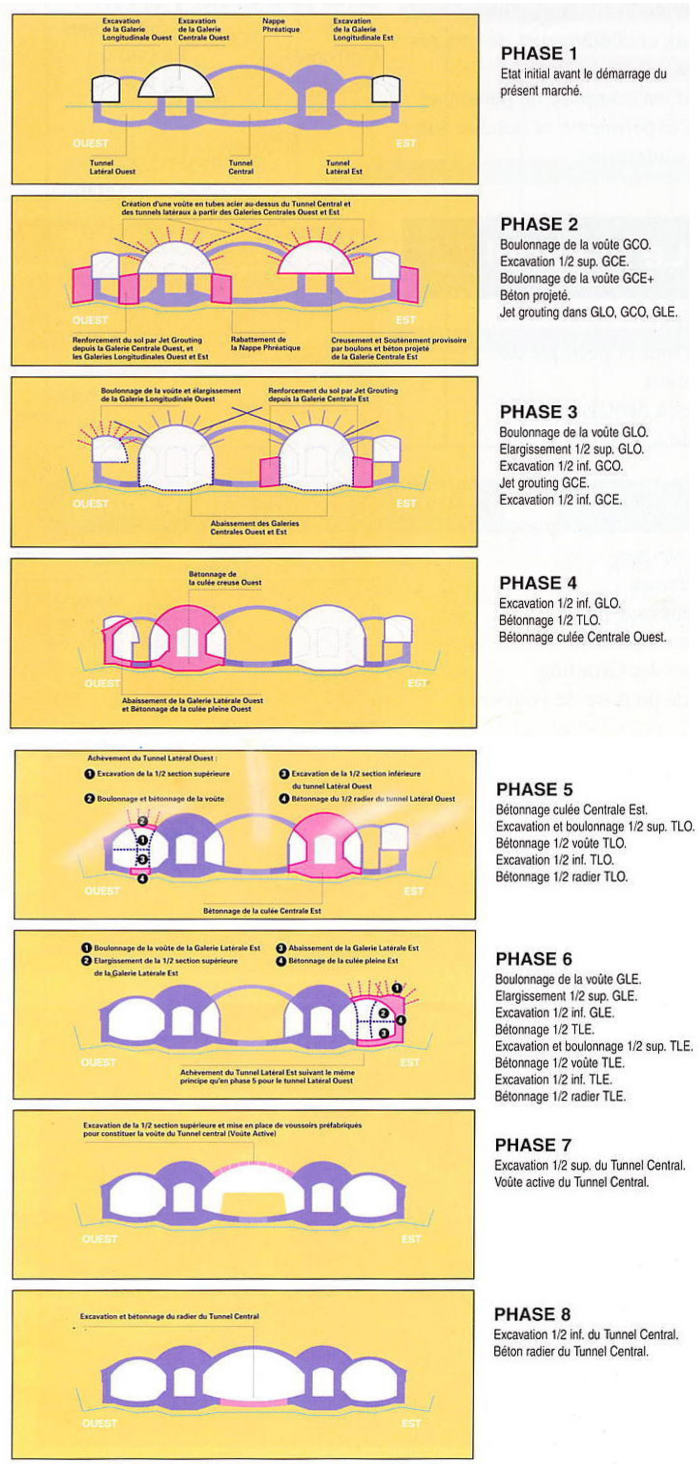

Fig. 5: Excavation sequence of the Magenta station

The construction principle was based on pursuing a precise order: realization of the abutments in underground over the entire length of the station through the exploratory tunnels already excavated, and realization of the foundations of the south concourse on the abutments.

The south concourse, a five storey underground structure, was excavated from surface after demolition of the existing building while preserving its façade as requested by the city's authorities.

The absence of available public spaces over the EOLE alignment, for its construction as well as for its future entrances, was the prime constraint determining the design of the project. Such underground stations and their connecting tunnels generate more than one million m^3 of materials to be excavated and disposed. Whereas the environment on the surface is only interlacing small overcongested arteries where the circulation of a chain of trucks loaded with mucks was not possible, so much for the respect of the residents than speed of operation.

Within the framework of the overall policy of environmental protection, the general organization of the project site attempted to privilege the supply of materials and the spoil removal in underground from and towards a railway yard located outside Paris, through the installation of a conveying belt from the east end of the alignment to its west end station (Figure 6).

The packaging plan and staging of work were subject to particular focus of study so that this umbilical cord was effective and operational as soon as possible in order to limit detrimental effects on the surface. With this intention, the contracts were allotted from north to south and east to west, in an order to allow expeditious construction of this continuous underground structure between the portal and the end station.

Fig. 6: Underground elevated conveyor belt

For the excavation of the two 1700 m long tunnels between the two stations, the use of a 7.4 m diameter slurry shield TBM seemed the most reliable technical response with a geological probing by radar ahead of the excavation face to detect the voids resulted from dissolution of gypsum (Figure 7). 0.35 m thick and 1.4 m long one pass gasketed concrete segmental liner was used as the tunnel liner. Each day, 6 rings consisting of 6 segments were installed and polyethylene dowels were used to connect successive rings. Tail skin grouting was applied to fill the gap between the excavated tunnel wall and the segmental liner ring.

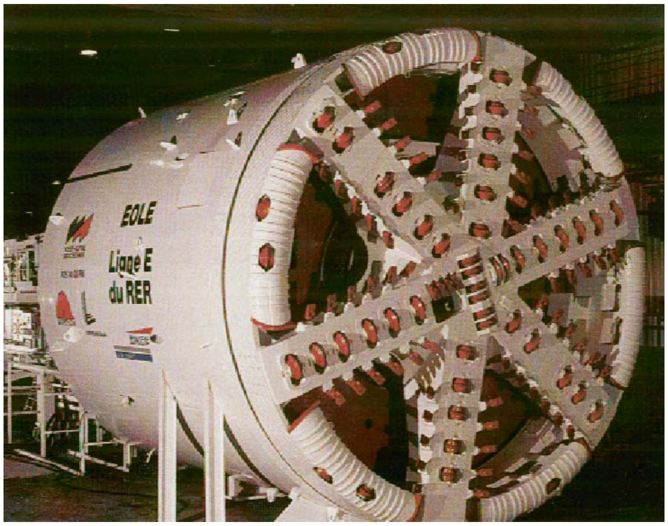

Fig. 7: Slurry shield TBM used for connecting tunnel excavation

APPLIED METHODS

A. Jet Grouting

After proceeding with in situ tests in two exploratory tunnels, the possibilities of conventional improvement of the Beauchamp sand under weak water head was excluded. At the same time, the jet grouting tests were carried out within the framework of the realization of the exploratory tunnels.

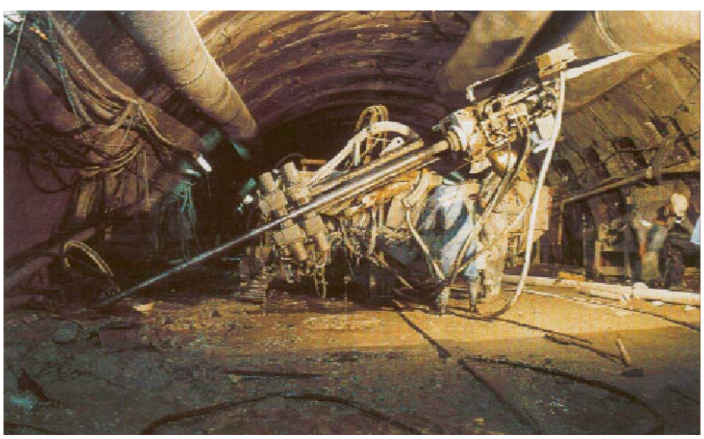

Fig. 8: Jet grouting from inside tunnels

The double jet technique was adopted to carry out the soil improvement under the abutments from surface.

A total of 4994 joined columns of 1 m diameter were carried out, representing 35824 ml of drilling and 19786 ml of jet (Figure 8).

The gained experience confirmed the importance of the sequence of execution of the columns with respect to the surface settlement.

B. Active Vault

The objective was to reduce the decompression of the ground by prestressing the arch supporting it, immediately after excavation, by a concrete structure placed on the two previously built abutments. In this method, large vaults can be carried out in full section.

The initial liner was installed at the same time as the final liner through prefabrication which made it possible to have a concrete element truly transferring the loads just after the excavation.

Open space between the vault and the excavation was filled by shotcrete, and then flat jacks positioned in the key segment were put in compression to push the arch against the ground resulting in reduction of future settlement. Then, a cement grouting was added to perfectly supplement the filling between the concrete arch and the ground.

This method was used under the name of Jacobson method for the vaults of the stations of the Paris express subway lines (RER A and B) in the 1970s and 1980s, as well as more recently for certain vaults of the stations or junction structures of Meteor subway line in Paris.

This choice, made by the French Railway (SNCF) from the beginning for the Magenta station, was particularly justified owing to the fact that the vault:

• had a large opening of 20 m span

• was very flat, because it was fixed by the geological horizon of Saint-Ouen limestone and proximity of surface

• was in subsoil of residential buildings, which required reliable solutions, guaranteed by the immediate support installation with an advance length of 1.20 m

• had 180 meters length which justified the use of a particular structure and a special procedure.

The key points of the method were:

• jacking procedure which ensured final stability of the structure and made it possible to limit settlements (at Magenta 400 tons per arch of 1.2 m).

• excavation limited to 1.20 m with careful support of the face: shotcrete, central block and bolts if necessary.

• speed of the sequence since the active support followed the excavation very closely.

• prefabrication which facilitated improved quality of concrete and reduced the arch thickness; here the vault had a constant thickness of 0.80 m, and made up of 11 segments of 3 to 5 tons articulated between them by a cylindrical fitting.

The installation machine had to ensure a certain number of elementary functions: handling and then installation of the segments without breaking them, assembly according to the shape of vault requiring a machine with free movement of joints, final adjustment against the preceding arc, access of the construction crew in vault for the installation of the waterproofing membrane, the shotcrete filling, the installation of the joints and the final jacking.

The installation machine lifted the prefabricated segments, placed and made them slide one after the other into their final position by a system of arm, carriage and jacks. It was also used to maintain the installed arch in place and in the desired form during the various phases preceding the final jacking. In addition, it gave access to the crew ensuring all the various operations to be carried out in vault through an arranged footbridge.

The excavation work was not constrained because the movement of the equipment and the access to the face were possible under the machine (Figure 9).

For the Magenta station the principle of the machine was entirely re-studied. Indeed, an architectural element in the shape of paneled ceiling was retained for the insertion of acoustic panels with the desire to represent the methods and techniques of work in the plastic expression, testimony of the know-how of our time.

Figure 9: Construction of the active vault

The characteristics of this architectural design were as follows:

• The intrados of the vault presented deep withdrawn of 1.6 m × 1.6 m with a pattern included the segments of two successive arcs.

• The pattern of the panels was reinforced by the presence of six longitudinal rabbets and thus did not allow auto correction, which occurs in the case of the segments with cross joints.

• The position of one panel at the axis of the vault imposed a staggering of the key segment by 1.60 m, alternatively on the right and on the left.

• The concrete placing between the panels of the abutments had to comply with the joints between arcs of the vault.

Because of handling operations being much more delicate due to the positions imposed for the key segments, the quality of the requested finish, the precision of installation required in alignment with the architectural joints of the abutments, also because of irregular withdrawal created in intrados, and of prohibition of anchoring on the visible finishes of the abutments, it was decided to assemble the entire prefabricated arc on the machine and to envisage inclined supports on the abutments in order to preserve freedom of movement in all three directions, for a final adjustment. This allowed an extreme precision with respect to the abutments concreted in the preceding phases under difficult conditions.

The machine, therefore, had to carry the total arc (50 tons) and maintain it adjusted within a tolerance of a millimeter with regard to the support of abutment during all the phases of adjustment and then of assembly without touching the abutments laterally.

After hardening of the special assembly mortar, the operations of backfilling with Shotcrete, jacking of the key and swelling of a waterproofing joint between arcs by cement grouting followed the excavation and support in vault and possible confinement of the face as well as the installation of an extrados waterproofing by P.V.C membrane.

The machine moved on rails installed on the abutment foundation at the platform level.

The cycle of advance of an arc had to be kept to less than 24 hours, to comply with the technical specifications of the contract. This duration was all the more difficult to adhere to, since for the first time in the case of a Jacobson vault, a waterproofing system of the membrane type was planned at the extrados of the segments. The installation time of this system being three hours, required to even improve the conventional performance of such an operation.

The problems of imbalance of the segments, alternative patterns of dissymmetrical arcs, increase in the lever arms and opening in the key of the vault led to important mechanical studies.

A total of 146 rings were carried out, intersected with the portions under the southern and central concourses, which were built in false arch to mask the elements of these structures.

Less than one week after the start, the installation of a ring every 24 hours as envisaged in the contract was obtained and maintained until the end (Figure 10).

Figure 10: Completed active vault

C. Umbrella Arch

Before constructing the vault of the central tunnel and portions of the vault of the side tunnels, for which certain zones were affected by geological problems, pre-support of steel pipes 82.5 mm in diameter and 12 m long grouted under pressure, and overlapped at the crown of center vault, was carried out to constitute a roof. Thus, 5526 ml of forepoling pipe was used.

D. Retaining Walls of Southern and Central Concourses

The simultaneity of the installation of concourse columns with underground work, with their exceptional length of up to 40 meters, together with the significant loading at the limit of buckling during the construction, in particular those of the Southern Hall, contributed to the realization of an exceptional support system.

Four machines in a very restricted right of way set up 4.400 ml of HEB 360 to 450 soldier piles.

E. New Austrian Tunneling Method

The traditional principles of the sequential method led to the successive construction of the galleries, and then vaults of limited opening, supporting them and concreting the structures which were gradually supporting one another.

New Austrian Tunneling Method (NATM) was retained for the multiple drifts of these galleries and vaults. It was applied for the first time in the Parisian geological context for such a big job in inhabited zone.

Immediate and systematic support in shotcrete, associated with bolting and some light steel sets, was designed following the calculations based on the principle of the participation of the ground itself in the constitution of vaults for which the resistance was improved by the confinement and by the anchoring increasing the shear strength.

This interaction between passive ground and active ground was observed by monitoring of the excavations: measurements of convergence and settlement in underground, measurements of settlement on the surface and geological follow-up.

The NATM went hand in hand with a certain number of technical choices:

• The jet grouting made it possible to consolidate the sand of Beauchamp to be used as support for the arch, to ensure lateral stability at the opening of the sidewalls, and to reduce the permeability of the soil mass under the water table.

• The dry shotcrete was prefabricated and admixtures were added industrially, which presented a clear quality advantage.

• A centralized installation, sound and dust proofed made it possible to handle this material, from storage to spraying after mixing with or without steel fibers, according to needs and at any hour of the day or the night, then to send it by a complete network of distribution in any point of the underground work site.

• More than 40000 m^2 of shotcrete was thus put in place at the 4 corners of the job site.

• The steel fiber addition allowed the removal of the welded wire mesh of first layer and improved immediate confinement in fully safe conditions.

• The bolting using Superswellex bolts with continuous and instantaneous mechanical anchorage of a force of 20 tons was a technique which proved very adaptable to the type of ground encountered and the need for easy cutting at the time of later excavation sequences. It was also possible to check the long-term behavior of these bolts. 45000 meters of these bolts were installed.

• The monitoring in real time, performed by 6 to 8 people, allowed the immediate follow-up of convergences and settlements with a significant number of measurements with optical devices. The daily analysis made by the contractor and the SNCF allowed the adaptation of support system and the excavation sequence as well as the study of the phenomena through back analysis with respect to the design predictions and at the same time with a preventive goal.

• The organization of quality turned around the technical follow-up of construction accompanied by a computer network providing real time monitoring on the job site and in the office.

These modern techniques took part in the execution of large volumes of this station.

DEALING WITH LARGE VOLUMES

The realization of large volumes was a consequence of an architectural desire to conceive wide spaces, ready to support the passage of crowd and to improve the visual expression of the structures through remote reference marks guiding the passengers.

It is interesting to note that these volumes were obtained, not only by the work carried out from surface, but also by work performed completely in underground.

For the structures constructed by the open cut method, such as the southern concourse, or below decking under street like the central concourse, the realized volumes were related to those of a conventional building where the transparencies between volumes ensure the legibility of the structures.

However, the transparency of the structures finds its limits vis-à-vis the determining criteria of ground pressure, settlement of the adjacent buildings and permanent and operational loads. The permanent and visible strut system offered an interesting response to these constraints.

Struts and posts were laid out judiciously to release a volume of 18 m wide 29 m long and 27 m high below the glass roof of the southern concourse, opening the perspectives to the passengers reaching the structure.

For the portions carried out in underground, like the tunnels in the station and the central concourse gallery, the good fitment of spaces of different sections was essential to the field of vision due to their arched form.

MONITORING SYSTEM

During the construction, the soil movements were monitored by an impressive program of monitoring. This helped to interpret the movements, to understand the influence of different phenomena involved and to make decision on construction aspects, such as adaptation of excavation sequence and support system.

Three to four thousand measurements per month with a precision of $\pm 3\,\text{mm}$ were recorded in an area of 15,000 m^2. More than 370 markers were stick on the façade of about 50 buildings (Figure 11). The minimal frequency of readings was monthly, but it became daily for the zone of underground excavation. Alert and limit thresholds were defined for these measurements.

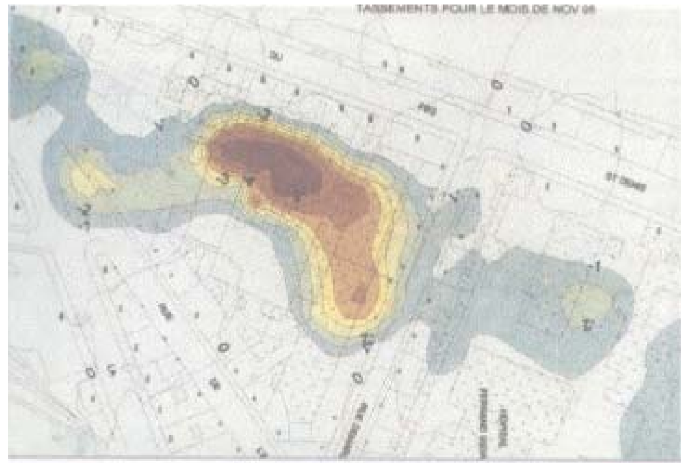

Figure 11: Surface settlement contours

The data obtained from the vibrating wire extensometer presents the real deformation of the structure. Knowing the time variation of temperature of the structure permits separating the mechanical and the thermal deformations.

(Bochon, 1992) proposed a method for the interpretation of the data obtained from the vibrating wire extensometer. In order to validate this method, and to apply it in the interpretation of the extensometric data of the Magenta Station site, the measured deformations of the East lateral tunnel liner during the construction of the active vault of the central tunnel was compared with the numerical analysis results.

During the construction phases of the active vault of the central tunnel, all station structures were subjected to large deformations. These deformations are presented in Figures 12 and 13. Figure 14 shows the deformations recorded by the extensometer for the East lateral tunnel.

Within the structure, the compression and tension zones generated by bending moment (resulted from the structure movement) can be seen. Positive moments at the invert central wall connection and roof central wall connection can be observed. These moments resulted from the difference in settlement of the central and lateral walls. The moment in the invert is higher than that in the roof, because of the combined effect of the differential settlement between the central and lateral walls, and the action of the higher passive earth pressure on the invert. Positive moment compresses the upper fiber of the beam. At the invert lateral wall connection and roof lateral wall connection negative moment can be seen.

To verify the extensometer measurements, a two-dimensional analysis using the finite element software CESAR-LCPC (Humbert, 1989) and by applying a differential settlement between the two walls of the tunnel was performed. The differential settlement was introduced by applying a vertical displacement on one of the walls equivalent to the differential settlement recorded by the leveling inside the tunnel. In this model the soil has a passive action on the tunnel, which means that the initial stress state around the tunnel is not generated.

The results showed a good agreement in term of compression and tension zones with the data obtained from the vibrating wire extensometer. This allowed to validate the interpretation of the vibrating wire extensometer measurements; and at the same time showed the importance of having these devices installed in the tunnel.

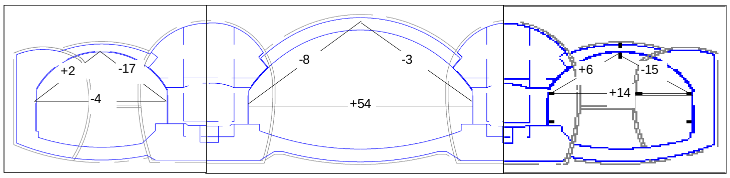

Fig. 12: Observed convergence for the station in 1/10 of mm

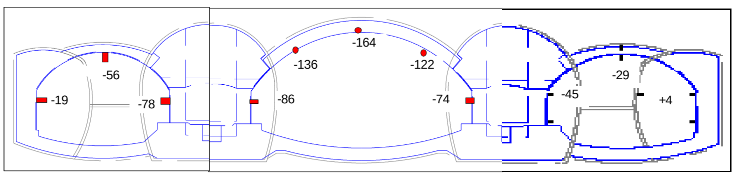

Fig. 13: Observed vertical displacements for the station in 1/10 of mm

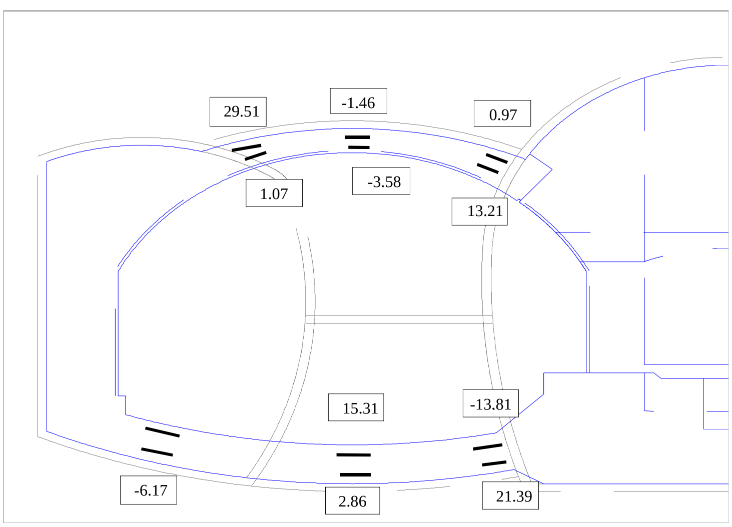

Fig. 14: Extensometric deformations in μm

CONCLUSION

EOLE project showed that it was possible to effectively build large underground spaces in a difficult urban environment by combining in a balanced way, the operational constraints, technical possibilities and architectural requirements. In this respect, the richness of possibilities offered by concrete to provide satisfactory solutions to the problems of complex construction encountered in this project should be emphasized.

The engineers' technical answers to the requirements of the architects proved that the typical conflicting concern of finishes and technical details can also exist in the field of tunnel design and can be resolved satisfactorily through the adherence of all, which could be the sign of a change in underground work.

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