Settlement Management for Urban Tunnels: An Example from France

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ABSTRACT: The TOULON highway tunnel is located in a very dense urban environment, and a much complex geology. The excavated section is about 120 m^2 and the depth is in the range 15-35 m. The aim of the paper is to show how a great attention was paid to the settlements control: at the design stage through soils investigations, survey of existing constructions in regards to their sensibility to tunnel induced settlement, definition of settlements thresholds, and choice of ground pre-reinforcement techniques; during the construction, by heavy monitoring of deformations and continuous adaptation of the supports to the actual settlements and buildings behavior. This case history is an illustration of how the settlements induced by tunneling can be managed for any urban tunnel, mainly in old cities.

KEYWORDS: Tunneling, Settlements, Monitoring, Compensation grouting

1. INTRODUCTION

Many cities in Vietnam have a very dense and ancient urban development, but also a urge need for infrastructure projects, particularly metro lines. Such developments require underground works, which are as much difficult as the ground is often of poor geotechnical quality and the existing buildings at ground level much sensitive to deformations induced by tunneling. Underground projects will therefore require a good management of the settlements. This paper presents a case history of a tunnel in south of France which was built between years 2007 and 2011, with many similarities to Vietnamese projects: difficult ground conditions, old urban environment.

The south Toulon tunnel connects motorways A50 and A57 from Nice to Marseille (Figure 1). It is parallel to the North tunnel previously built between 1994 and 2000, during construction of which large settlements were observed, inducing some cracks in the buildings, and a sinkhole occurred fortunately in a non constructed area. The question of how to control the tunnel induced settlements was therefore an outstanding priority for the south tunnel.

Figure 1 Toulon South tunnel location

The tunnel has a 120 m^2 section and is 1820 m long. The overburden is rather small, between 15 m and 35 m maximum, and the tunnel is below the sea level.

The tunnel construction presented from the design stage high difficulties, starting from the poor characteristics of encountered ground, very difficult heterogeneous and tectonized soils and rocks, and due to the very sensitive urban environment, with narrow streets and old buildings all along the alignment.

In this context the choice was done for the construction method of a full face conventional excavation associated with ground reinforcement ahead of the tunnel face by pipe umbrellas and face bolting.

This construction technique induces complex interactions between the ground, the support of the tunnel (steel ribs and shotcrete), the ground reinforcement ahead of the face (umbrella pipes and face bolts), and the surrounding existing structures. In such conditions it is much difficult to accurately predict the induced settlements and their effects on the existing buildings.

It is the reason why a great attention was paid to control the settlements, both at design stage by detailed investigations and modelizations, and during construction by developing a efficient system of monitoring and methods for adapting in real time the construction sequences and the amount of reinforcement to the measured settlements.

It is hoped that such case history can be useful for the new tunnels to be built in Asian old cities, where both the sensitivity of existing constructions and the poor quality of ground is a major challenge for geotechnical engineers.

2. DESCRIPTION OF THE PROJECT

2.1 Geology

One of the most important difficulties of this project is the Toulon geology. A large number of geological investigations (core and destructive drillings, in situ testing and laboratory tests) were performed, which showed very heterogeneous ground all along the tunnel layout (Figure 2) and even at the tunnel face scale (Figure 3).

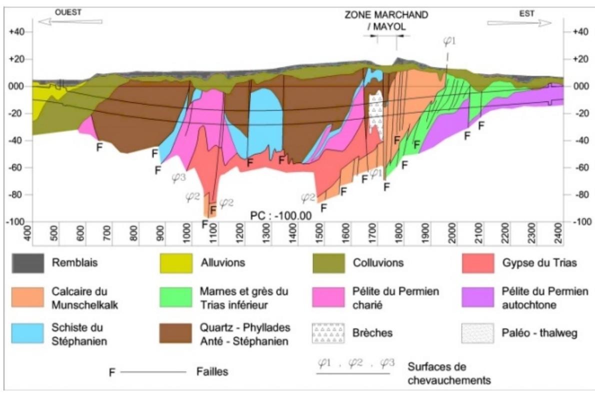

Figure 2 Simplified geological profile

They identified more than ten different soil or rock types, changing all along the tunnel due to intense tectonisation (thrust phenomenon): weathered quartzophyllite, claystone, gypsum, karstic limestone, breccia, etc..

The GSI rate of these grounds is mainly about 20-30, revealing very poor tunneling conditions. Regarding the deformation modulus E, of main concern for settlements aspects, it was thoroughly investigated though pressuremeter testing, as the small scale heterogeneities could not allow representative measures from lab samples. Design value of E ranged from 50 to 150 MPa.

As a consequence of these high geological variations, additional horizontal investigations are done from the tunnel face all along the tunnel progress. In addition, the geologists control and analyze the tunnel face after each excavation step before shotcreting (Figure 3), in order to anticipate how the geology could change in the following meters.

Figure 3 Geology at the face.

2.2 Excavation method

A full face excavation method has been chosen in order to better control the surface settlements.

The excavation progresses generally by 1.5m steps. After each step, one HEB 180 rib is installed and the ground between ribs is lined with shotcrete 25 to 30 cm thick. A closure invert made of HEB 220 ribs and shotcrete is realized either immediately or with some delay depending on ground deformations.

In addition to this conventional support, the ground mass ahead of the tunnel face is reinforced by pipe umbrella and face bolting with varying densities. Figure 4 shows one of the most commonly used support profile.

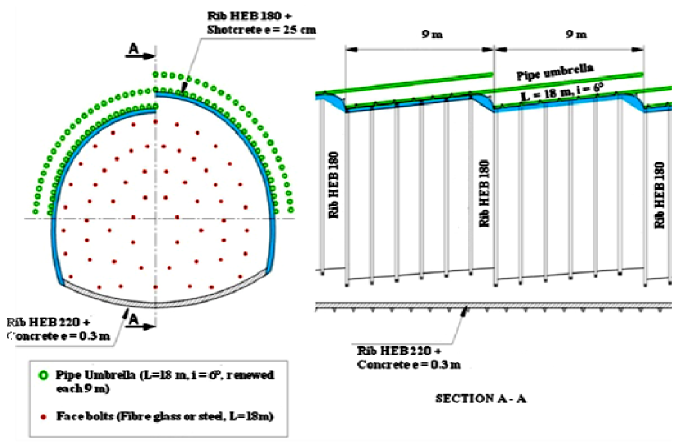

Figure 4 A common support profile

Table 1 summarises the main characteristics of reinforcement bolts (average values). In fact, density, length and renewal vary continuously depending on soil conditions and settlements previsions.

Table 1 Reinforcement characteristics

Item	Umbrella pipes	Face bolting
Material	Steel	Fiberglass/Steel
Length	18 m	18 m
Slope	6/14°	0°
Renewal	9 m	4.5/9 m

This excavation procedure is based on the so-called "ADECO-RS" method developed by Lunardi (2008). Lunardi understood that protecting and improving the strength and stiffness of the ground ahead of the tunnel face, the "core", allows realizing full face excavations of tunnels even under very difficult ground conditions. This methodology allows to increase tunnel stability and to reduce tunnel deformations and surface settlements in case of shallow tunnels.

In Lunardi's theory, the role of the pre-reinforcements ahead of the face is to prevent the loosening of the core, and to maintain its peak characteristics. He describes two mechanisms of interventions for ground "conservation":

- Protective conservation: the pre-support have to channel the stresses around the advancing core in order not to overload and over-deform it, therefore maintaining its natural strength and deformation characteristics. In our case, it is the role of the umbrella tubes.
- Reinforcement conservation: the pre-support improves directly the natural strength and stiffness of ground in the core. Horizontal fiber-glass bolts are used and are one of the keys for the success of this technology: they exhibit high axial strength but are brittle, allowing to be easily cut by the excavation tolls.

The design stage consists in a geological analysis of the ground all along the tunnel alignment, a division in sections with uniform stress-strain behavior, and finally the choice of the type of reinforcement to be applied by considering such predictions.

At the construction stage, after realization of stabilization works based on design predictions, a continuous monitoring of the deformations in the tunnel and at the ground surface is implemented (see Figure 5).

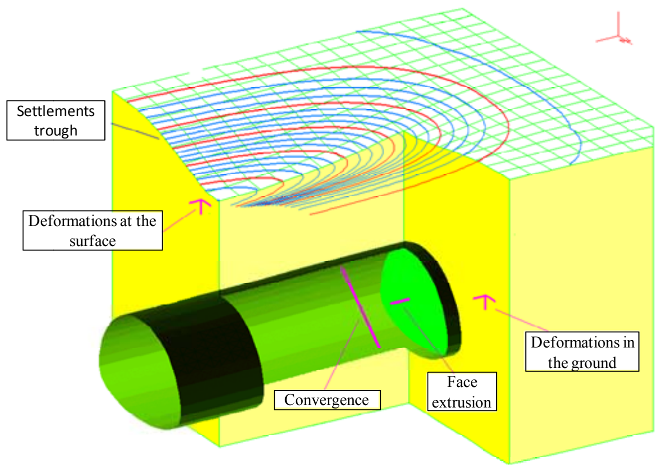

Figure 5 Ground deformations and surface settlements during excavation of a shallow tunnel

The observed ground response is compared to the predicted one and necessary adaptations (on support and pre-reinforcements) are done to guarantee the excavation stability and limit the surface settlements.

3. MAIN DESIGN CRITERIA OF THE PROJECT

Moreover than simply ensuring the stability of the tunnel, the main design criteria were the limitation of induced deformations to values allowable for the buildings existing at the ground level.

As a large part of these buildings are old ones, they are more or less sensitive to settlements. Therefore an intensive structural survey of all the constructions located in a 100 m wide range above the tunnels was performed, in order to check their foundations, the possible existing damages (cracks, tilts, etc) and to classify these buildings.

Then thresholds for total and differential settlements were proposed for each one of the 15 « homogeneous » area selected according to: (i) the sensitivity of the existing constructions, (ii) the depth of the tunnel (iii) the geotechnical behavior of the ground, mainly the stiffness of the different layers. Three kinds of thresholds were defined, "Vigilance – Anomaly – Alert", with values varying on the different area of the project, and actions were proposed for each level (see Table 2).

Table 2 Settlement thresholds

Threshold	VIGILANCE	ANOMALY	ALERT
Diff. settlement	1.2 to 1.5 /1000°	1.5 to 1.8 /1000°	1.8 to 2.0 /1000°
Total settlement	22 to 44 mm	26 to 55 mm	29 to 66 mm
Actions	Check the measure and look for the causes	Design and immplement additional reinforcements	Stop the works to avoid damages and restart after reinforcements

The principle of the work supervision was to analyze in real time the actual settlements measured through numerous monitoring equipment's, and to adjust the reinforcement to be implemented to these actual settlements: increasing the amount of (pre)support when settlements tend to exceed the thresholds, or decreasing the (pre)supports when deformations are anticipated to be below the allowable values.

Of course such goal required a very accurate system of monitoring, and to develop a method for estimating the final settlements as soon as possible, when only the beginning of the settlement curves is known.

4. REAL TIME PREDICTION METHOD

The settlement trough caused by the tunnel excavation is tridimensional. The traditional methods of settlements previsions are based on the study of surface subsidence in a transverse section perpendicular to the tunnel axis. During the Toulon tunnel works progress, such analysis on transverse sections is regularly made, especially when the excavation is done under sensitive buildings, but it was only possible in the few streets perpendicular to tunnel.

This is why the pre-reinforcement and support adjustments are essentially based on the settlements previsions carried out from the movements observed ahead of the tunnel face. For this purpose, it is essential to find a way for estimating the final surface settlements, which includes an automatic system for measurements and a theoretical method for extrapolating the settlements curves.

4.1 Automatic system for settlement measurements

An automatic system of ground level and buildings settlement measurements has been set up by SOLDATA. These measures are combined with a regular control of tunnel deformations (convergence and face extrusion).

The principal objectives of such monitoring are: (i) to guarantee the short term tunnel stability and therefore the workers security, (ii) to verify the impact of excavation on buildings and to avoid damages, (iii) to assure the long term stability and serviceability of the tunnel.

The settlements monitoring system consists in automatic stations that measure the ground surface and building deformations with a high frequency. A transverse profile is defined every 9 m along the whole tunnel layout. There are two different approaches for measuring the ground settlement from the automatic stations (see Figure 6 and Table 3):

- Recording the vertical movement Z of virtual points positioned on a horizontal grid without the need for targets, collected once per day through CENTAURE system,
- Recording the whole movements in X, Y, Z directions of prism targets, fixed on buildings, every two hours with CYCLOPE system.

The accuracy of both systems is about 0.5 mm. In addition, in order to avoid systematic errors, the automatic stations are regularly calibrated against target prisms which are considered as fixed because far from the influence zone of excavation progress.

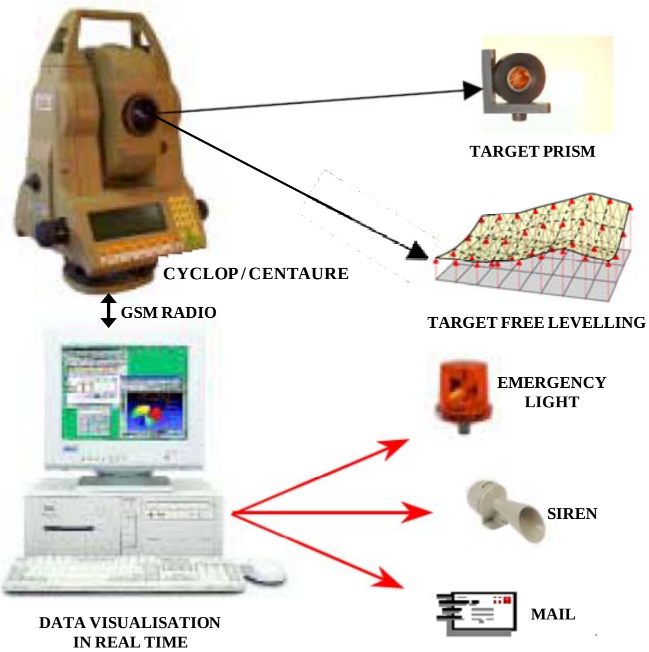

Figure 6 CYCLOP and CENTAURE measurement systems (SOLDATA)

Table 3 Automatic monitoring systems characteristics

System	CENTAURE	CYCLOP
Measure	Z	X, Y, Z
Frequency	1 measure/day	1 measure/2 hours
Accuracy	± 0.5 mm	± 0.5 mm

All data are immediately centralized in a geographical information system and recorded in a PC database, which contains also tunnel deformations measurements and other important information's, such as geological tunnel face surveys, piezometer measurements and tunnel work progress.

Thanks to a remote access, the project team can connect onto the database and analyse in real time the monitored data from their offices (Figure 7).

Moreover, in order to facilitate the analysis of the measured movements, automatic curves are generated and available on the webpage. And, regarding the works security, two types of alarms can be automatically generated: in situ alarms (emergency lights and sirens) and e-mails sent to project participants. Thus, in case of unforeseen events, rapid action can be taken.

In Toulon project, the adjustment of the tunnel process was based mainly on the prevision of surface settlements developing on the tunnel longitudinal axis, according to the methodology described in the following section.

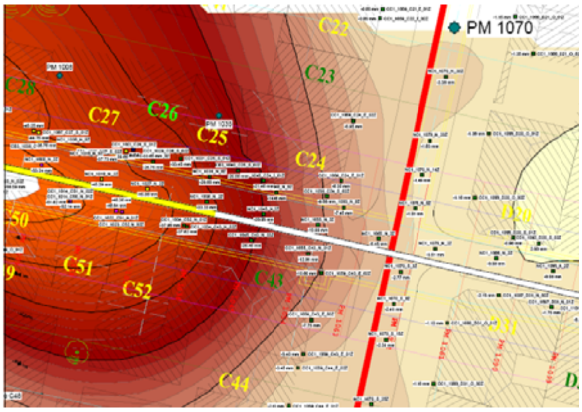

Figure 7 View of the real time database output (settlement through)

4.2 Models describing the settlements on the tunnel axis

Figure 8 shows the settlements longitudinal profiles of three surface points above the tunnel axis against their distance from the tunnel face, done when the face was at chainage PM 1081:

- The surface point PM 1095 is 14 m ahead of the face and already settled down by 10 mm;
- The point PM 1075 is 6 m behind the face with 25 mm of settlement;
- The settlement of point PM 1018, placed 63 m behind the face, stabilized at 55 mm.

The graph shows that deformations at ground level begin approximately 30 m ahead of the tunnel face (approximately equal to the tunnel depth), and that more than 40% of surface deformations occur ahead of the tunnel face.

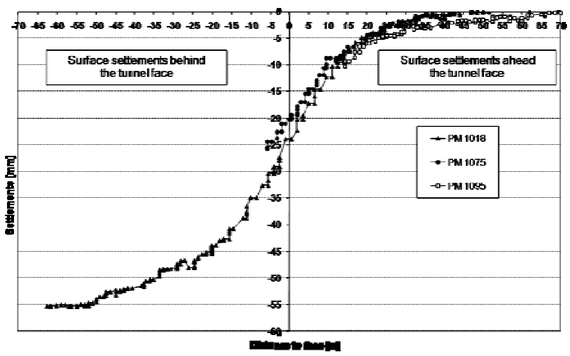

Figure 8 Settlements of three surface points caused by the excavation advancement

An efficient settlement prediction requires either developing 3D numerical models for many sections of the tunnel, which is not practically performant, or using an empirical equation that is able to describe the development of surface settlements on the tunnel axis; this second method was chosen in this case.

After selecting such empirical model, the prediction method during the excavation progress consists in calibrating the parameters of the model with the first settlements measured ahead of the tunnel face. This optimization can be repeated whenever new data are collected with the tunnel progress, allowing a more and more accurate prediction of the final settlement.

A normal exponential type equation is often used to describe the trend of settlements along the tunnel axis. Several others proposed improvements of such equations:

- Grasso and Pelizza (1994) proposed to represent the settlements evolution against the distance from the tunnel face with an exponential equation depending on the tunnel overburden.
- Dubois and Jassionnesse (1997) analyzed the measurements of North Toulon tunnel and suggested that the settlement of a surface point, caused by a "source" (the excavation of a section of the tunnel), is proportionally controlled by the source deformations and inversely proportional to the square of the distance between the point and the source.
- Serratice and Magnan (2002), still from the North Toulon tunnel data, proposed the following semi-empirical equations for the settlements evolution (S) against the distance between the point considered and the tunnel face (x):

$$S(x) = 0 \;\; for\; x > x_0 \tag{1}$$

$$S(x) = S_0 \times \left[1 - exp\left(-A \times X^2\right) / \left(1 + X^2\right)\right] \;\; for\; x < x_0 \tag{2}$$

$$\text{with} \;\; X^2 = \frac{(x - x_0)^2}{H^2} \tag{3}$$

$$A = \frac{\alpha \cdot H^2}{(R + H)^2} \tag{4}$$

where, x_0 is the distance between the face and the point at ground level where the settlements start to appear; S_0 is the maximum settlement expected and R and H respectively the tunnel radius and depth. They calibrated the parameter α to 0.25, leading to a model with only two unknown parameters, S_0 and x_0.

- Bourgeois (2002) carried out 3D Finite Element analyses to simulate the North Toulon tunnel excavation and proposed the following equations to represent the numerical results:

$$S(x) = S_f \times \left[1 - th(x / D_+\right] \text{ for x} > 0 \tag{5}$$

$$S(x) = S_0 \cdot \left[1 + \left(S_f / S_0 - 1\right) \cdot \exp\left(x / D_-\right)\right] \text{for x} < 0 \tag{6}$$

$$D_- = D_+ \cdot (S_0 / S_f - 1) \tag{7}$$

S_f, S_0, D_+ represent respectively the settlement at ground surface above the tunnel face, the expected final settlement and the extent of the settlement trough ahead the face.

Both Serratrice-Magnan and Bourgeois models were tested on the settlements measured during the South Toulon tunnel excavation, together with another empirical model (Janin, 2011), still based on the usual exponential equations (equation 8):

$$S(x) = 0.5 \times S_0 \times \left\{1 - th\left[\left(\frac{k}{i}\right) \times x\right]\right\} \tag{8}$$

where, S_0 is the estimated final settlement ; the ratio k/i regulates the curve shape; i is the parameter of the normal Gaussian function used to describe the shape of the settlement trough in a transverse section representing the distance from axis to the point of inflexion of the settlement trough; k is a dimensionless parameter; x is the distance, at a given moment, between the point considered and the tunnel face.

Finally, in order to obtain a better approximation with the South Toulon data, the previous expression was modified, introducing an additional parameter a, a translational parameter modifying the ratio S_{face} / S_0. Therefore, the equation becomes (9):

$$S(x) = 0.5 \cdot S_0 \cdot \left\{ 1 - th\left[\left(\frac{k}{i} \right) \cdot (x + a) \right] \right\} \tag{9}$$

The optimization by the least square method of three different models shows that the modified approach proposed in Eq. 9 gives the best results in the case of the South Toulon tunnel (see Figure 9), and has been chosen to make the final settlement predictions.

In fact, as shown in the example on Figure 9, it is possible to obtain a good approximation of the settlements progression behind the tunnel face (x<0) with both Serratrice-Magnan and Bourgeois models. Nevertheless, they are not able to accurately represent the settlements ahead of the tunnel face (x>0).

On the opposite, with the modified model, the adjustment of the three free parameters (S_0, ratio k/i and a) on the settlements observed ahead the tunnel face leads generally to a better estimation of the settlement evolution with the tunnel advance and of the final settlement.

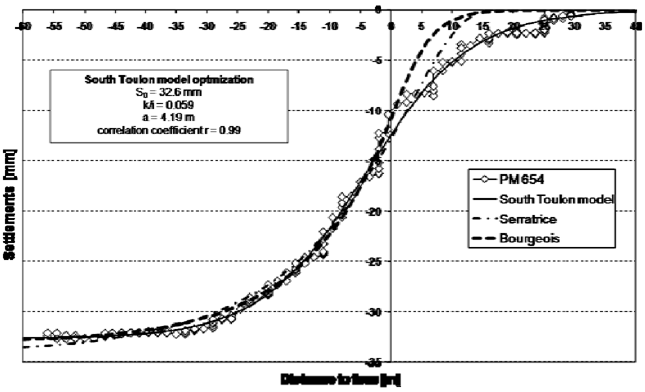

Figure 9 Evaluation of three models on a case of South Toulon tunnel settlement measurements

4.3 South Toulon tunnel settlement thresholds

In addition to the settlements predictions, the modified approach is also used, for each homogeneous area, to draw the three curves corresponding to the three settlement thresholds, as described in chapter 3. In this case the S_0 parameter is imposed while the other two parameters (k/i and a) are chosen in order to fit the curve on the settlement trends of the concerned area.

The real time comparison of the predicted settlement curves with the three threshold curves corresponding to the area is the basic element of the adjustment of tunnel process. Actually, the project contract imposes the following conditions:

- if the settlement prediction curve is smaller than the vigilance threshold one, a reduction of the pre-reinforcement is recommended;
- if the settlement prevision exceeds the anomaly curve and come close to the alert one, it is necessary to change the tunnel process, increasing for instance the pre-reinforcement, in order to limit further settlements and stay close to the anomaly threshold.

In order to economically optimize the works progress together with avoiding building damages, the tunneling process was continuously adapted by trying to fit the settlement evolution on the anomaly curve. An example of this approach is presented in the following section.

4.4 Example of tunnelling process adaptation on settlements prediction

Figure 10 shows the study on the settlements evolution of a Toulon area performed when the tunnel face was at chainage PM 820.

The three points at PM 766, 782, 802 started their settlement ahead of the face (x > 0) with a worrying trends close to the alert curve.

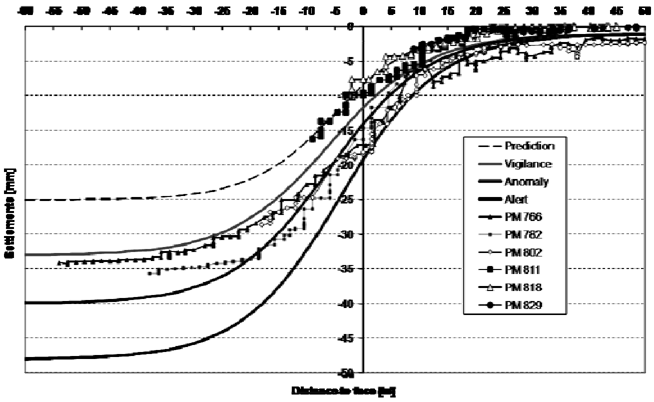

Figure 10 Example of tunneling process adaptation on settlements predictions

Simultaneously, during the excavation between the PM 758 and PM 792, tunnel face local instabilities often occurred. For these reasons, and in accordance with the project contract, the following modifications of the tunneling process were applied:

- umbrella pipes number was increased from 21 to 33 and their inclination decreased from 14° to 6°;
- the face bolting was improved with 15 self-boring steel bolts, 9 m long, grouted with resin;
- the face tunnel was excavated in 5 successive steps in order to limit the instabilities.

These countermeasures permitted to decrease the face tunnel instabilities but also to reduce the surface settlements evolution. actually, the settlements trends of the three analyzed points returned, for x < 0 (behind the face), toward an acceptable tendency between the vigilance and anomaly thresholds curves, with a final settlement of about 35 mm.

After having passed this difficult zone, the ground conditions improved and the settlements trends of the points around and ahead the tunnel face (PM 811, PM 818 and PM 829) got better as well. As shown on Figure 10, the prediction curve for these points, done when the tunnel face was at PM 820, led to a final settlement of 25 mm, smaller than the vigilance threshold. Therefore, the team project decided to modify once more the tunneling process in order to economically optimize the pre-reinforcement: the umbrella pipes were substituted with "smaller" bolts, the face bolting was lightened and the rib invert was cancelled.

As a synthesis of all these data, Figure 11 is the superposition of settlement curves at ground level above the tunnel axis for different dates over a 600 m long section of the tunnel. It shows how the final settlements varied very quickly: they ranged between 20 to 60 mm, sometimes within 50 m distance, without any direct relationship with geology, but mainly with intensity of pre-reinforcements.

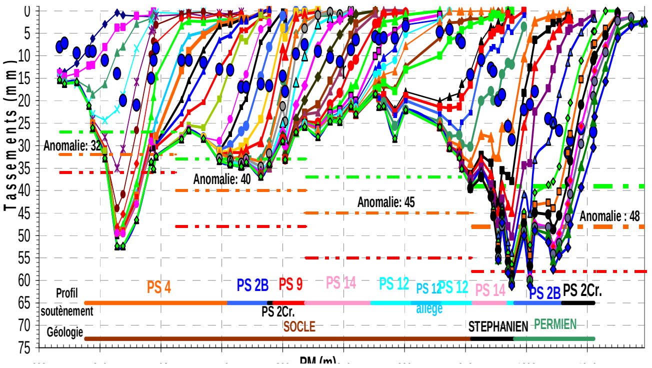

Figure 11 Longitudinal profile (partial) of final settlements

4.5 Surface settlements analysis in the transverse sections

During the South Toulon tunnel excavation, in addition to the analysis of settlement evolution at ground level above the tunnel axis, the trends of the surface subsidence in transverse sections have also been considered. Numerous studies, starting from Peck (1969) proved that the settlements (S) can be described with a good approximation using a normal probability Gaussian function (equation 10).

$$S(x) = S_{\max} \exp\left(\frac{-x^2}{2i^2}\right) \tag{10}$$

where, S_{max} is the maximum ground surface settlement above the tunnel axis; x is the horizontal distance to the tunnel axis and i is the standard deviation corresponding to the distance between the point of inflexion of the settlement trough and the tunnel axis.

It is very important to estimate the position of the point of inflexion, as the i value corresponds to the area in which the settlements curve presents a curvature change and the subsidence profile slope (β) is maximum. Besides, it separates two zones in the ground above the tunnel: an extension zone over the convex parts of the settlement trough and a compression zone over the concave parts. The building is subject to different solicitations depending on its position in the above mentioned zones.

Different authors studied the effects of differential settlements on the buildings. Former researches, based on the observation of 98 buildings, showed that it is necessary to reach a value of β equal to 1/150, in order to induce significant damages in the concrete structures. More cautious allowable values are proposed in Eurocode 7: β equal to 1/500 for reinforced concrete framed structures and 1/200 for open frames.

Figure 12 shows an example of the analysis of the movements measured in a street perpendicular to the tunnel axis. The two different monitoring systems were available in this street: virtual points at ground level (CENTAURE) and target points on the buildings (CYCLOP). The calibration of the parameters S_{max} and i of Peck's approach for the transverse trough has been conducted on both sets of values with the least squares method.

The different buildings (C35, C60, etc...) are also shown with their respective positions relative to the tunnel axis. In both data sets, the values of i are the same: 20 m, which allows locating the two points of inflection of the settlement trough and comparing them with the buildings position. The result is that, in the example, the most critical consequences could appear at the contact between buildings C34 and C33 on north side of the tunnel and between C60 and C59 on south side. But in this case, the maximum slope was low (0.8 to 1 mm/m) and no damage appeared in the buildings.

Regarding the maximum absolute settlements, the two calibrations diverge at the tunnel axis: settlements measured on the buildings (33 mm) are larger than at the ground level (27 mm). This is a consequence of the soil-structure interaction phenomena, the stiffness of the structure modifying the ground response.

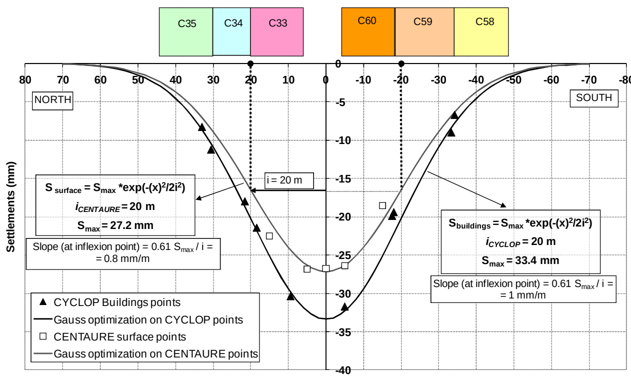

Figure 12 Gauss optimizations on transversal settlement measures

4.6 Differential settlements predictions

It is well known that the development of both total and differential settlements have to be analyzed in order to avoid buildings damage. The measured differential settlement of a building is the ratio between the settlements difference and horizontal distance of two target prisms fixed on its structure. As for total settlements, the project contract imposes three threshold levels of final differential settlements. Therefore, it was necessary to elaborate a prediction method for these differential settlements, as well.

The proposed approach for the prevision of total settlements was tested on the differential settlements, and revealed that it was possible to use the same model than for the total settlements prediction (Figure 13): the method for predicting differential settlements is the same than that for absolute settlements, only by substituting in the equation (9) the parameter S_0 with the maximum predicted differential settlement ($S_{diff\ max}$).

The model is fitted on the first differential settlement measured ahead of the tunnel face, then eventually optimized as soon as new measures are obtained. The final differential settlement prediction, which becomes more and more accurate with the tunnel progress, is compared with the project thresholds values. Therefore, different decisions can be taken in order to fulfill the project contract requirements.

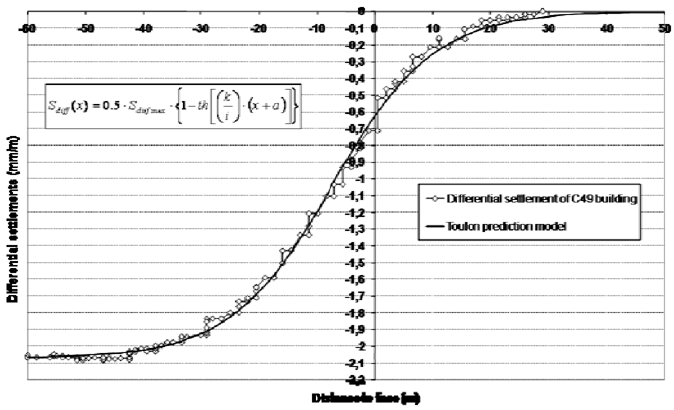

Figure 13 Model prediction of differential settlements

5. COMPENSATION GROUTING

The method of compensation grouting can be considered as a concept allowing coping with extreme cases of tunnelling in adverse ground conditions with highly sensitive buildings.

It was mainly developed in London in the 1990's for the Jubilee line metro excavation, in the deformable London clay, where the predicted settlements were in excess of 60 mm with usual tunnelling methods, which was obviously unacceptable for historic buildings such as the famous Big Ben Tower.

This concept can be qualified as "passive" as it does not look for sophisticated tunnelling techniques, but leaves the deformations occur naturally at the tunnel level, while compensating the settlements produced in depth by "creating heave" of the layers between the tunnel and the buildings foundations by means of bentonite cement grouting (Figure 14).

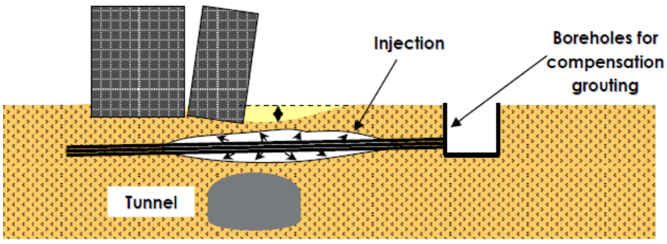

Figure 14 Principle of compensation grouting

Practically the method is implemented in three phases:

1) Prior to any excavation in the area, create a subhorizontal mattress, few meters thick, in the layers above the tunnel and below the foundations, by classical grouting. Such grouting is implemented from boreholes drilled at any available location or if not possible from shafts; this requires a lot of borings. The goal is to "prepare" the ground such as it reacts efficiently in the following phases;
2) A "conditioning phase" where the system is calibrated by grouting small quantities of grout, typically few tens of litres every meter of borehole, in order to check how a given volume of grout create a heave of the surface. Ratio of grouted volume to heave volume is generally in the order of 3 to 7, with an average value of 5;
3) Then the excavation can begin by introducing continuously, in real time as the excavation progresses, the quantity of grout required to create a heave of ground surface equal to the anticipated and observed settlement.

Such method, which requires a very accurate real time monitoring of deformations, allows keeping the surface settlements in a very narrow range, typically ± 5 mm.

This compensation grouting method was implemented for the Toulon tunnel (Guilloux et al, 2011): in a given area the excavation had to underpass an 8 storeys high building in a geologically very disturbed zone, where preliminary structural expertise's led to consider that allowable settlements were approximately 65 mm. Jet grouting was performed from the tunnel face, in addition to umbrellas and face reinforcement, with the purpose not to exceed these allowable settlements.

Nevertheless, when the tunnel face was about 10 m from the building, the settlements quickly increased up to about 40 mm, and some minor damages were noticed in the building. It was therefore considered that the building was much more sensitive than anticipated, and that it was not possible to go on with tunnelling without taking risks of more prejudicial damages.

After looking for solutions by structural reinforcement of the building, it was finally decided that compensation grouting was the best suited method to deal with the risk for the buildings and the inhabitants. 57 boreholes were performed from a small shaft dug in the vicinity of the building, with lengths varying from 40 to 55 m, on 3 levels in order to create a 4 to 5 m thick mattress (Figure 15).

The monitoring of the building was completed, in order to be able to check any kind of movements in real time.

Then the conditioning phase could be done; but as in this case, as the building had already differentially settled up to 40 mm, it was decided to re-heave the building in order to reduce its tilt prior to tunneling. Figure 16 shows the monitoring results of grouted volumes and vertical displacements of the building during the 40 days of this preconditioning and re-heave stage: a total volume of 50 m^3 grout was introduced resulting in an about 10 mm heave, with a strong correlation between both. The ratio between grouted volume and heave volume is about 6 during this conditioning phase.

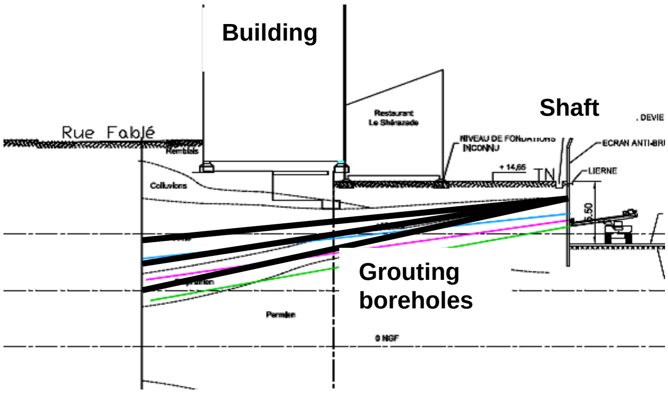

Figure 15 Cross section with location of boreholes for mattress

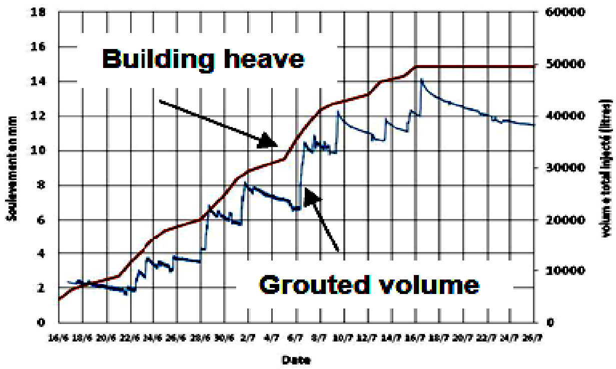

Figure 16 Results of preconditioning and reheave phase

The tunnel excavation could then resume: the difficult zone was passed within 2 months; the total grouted volume reached about 80 m^3, and Figure 17 shows that the vertical movements of the building remained constant during this phase of excavation, while the predicted settlements were between 30 and more than 50 mm.

This resulted to a ratio between grouted volume and effective heave volume of 2 to 3 during this compensation phase, much lower than the ratio of 6 observed during the conditioning phase.

Most impressive is the result that the vertical movements could be maintained in the range of ± 1 mm during the excavation thanks to the heavy monitoring and the continuous grouting.

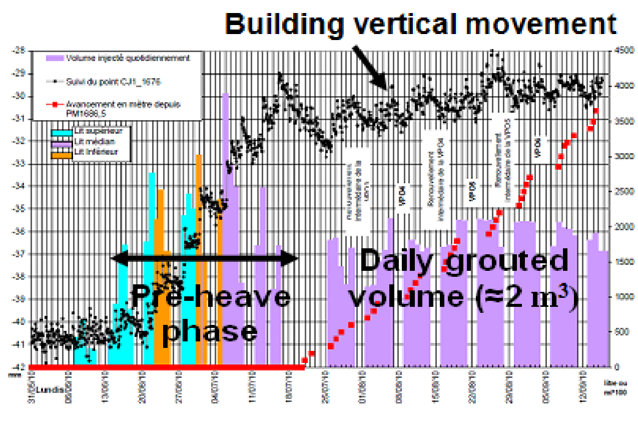

Figure 17 Results of compensation grouting during conditioning and excavation phases

6. CONCLUSIONS

The Toulon south tunnel was a very challenging project because of its difficult geological conditions and very dense and old urban environment, outstanding the question of settlements management.

Actually the basis of the design was not the stability of the tunnel, but indeed the limitation of the tunnel induced deformations: heavy supports, detailed investigations of existing buildings, allowance for high level settlements, up to more than 5 cm, sophisticated monitoring system.

The excavation was finally successfully achieved within about 5 years, without any noticeable damages on the constructions, except in one case where the compensation grouting technique was finally applied and revealed much efficient.

Such a success was only possible thanks to a strong cooperation between the Owner (French Public Road Authority), the Contractors (Bouygues, Solétanche Bachy…) and the Engineer (Setec TPI, Terrasol).

It can be considered as a reference of how it is possible to manage extremely difficult excavation and environment conditions by developing:

- Detailed ground and existing buildings sensitivity investigations, and modelization of the soil-structure behavior at the design stage,
- Contract obligations regarding the thresholds for deformations, together with actions to implement in case of excessive movements (increase of (pre)supports) but also in case of movements smaller than anticipated (decrease of (pre)supports),
- Thorough monitoring, at the construction stage, of the tunnel and ground level / buildings deformations, together with predictive models for final deformations calibrated in real time with measurements.

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