Geotechnical Aspects of Underground Construction in Soft Ground – Viggiani (ed)

Settlement monitoring and tunnelling process adaptation—case of South Toulon tunnel

J.P. Janin, D. Daniel & R. Kastner
LGCIE, INSA de Lyon, Lyon, France

F. Emeriault
Grenoble-INP, UJF-Grenoble 1, CNRS UMR 5521, 3SR Lab, Grenoble, France

A. Guilloux & H. Lebissonnais
TERRASOL, Montreuil, France

ABSTRACT: The construction of urban shallow tunnel induces deformations of soil that spread from the cavity and towards the surface forming a settlement trough. In urban zones, it is essential to control the volume and shape of the settlement depression in order to avoid damages on neighbouring buildings. This paper presents the case of the South Toulon tunnel, realized by a full-face excavation with soil reinforcement ahead of the face by a pipe umbrella and face bolting. This project shows how it is possible to regulate the tunnelling process (reinforcement and lining adjustments) by mainly considering the monitoring and the prediction of surface settlements. For this purpose a simple analytical equation, describing the development of surface settlements on the tunnel axis against the tunnel face progress, has been used. Some examples of this approach will be presented.

1 INTRODUCTION

The excavation of a tunnel produces a disequilibrium of the initial stress field in the ground mass, inducing soil deformation and settlements. Deformations of soil are triggered in the core ahead the tunnel face, and are later increased by the convergence of the excavated cavity. In urban areas, it is essential to control and minimize the settlements due to tunnelling in order to avoid damage on neighbouring buildings and other service networks. Therefore, predicting surface settlements becomes one of the most important key tasks in tunnelling process. For this purpose, some authors, as Dubois & Jassionnesse (1997), Serratrice (2002) etc, proposed different equations to model the progression of settlements on the tunnel axis for the 1st tube of the Toulon tunnel.

This paper reports data from the particular case study of the South Toulon tunnel. During its excavation, surface settlements are continuously monitored by automatic stations with a high frequency. The analysis of the measured movements shows that the development of surface settlements on the tunnel axis can be represented by a simple analytical equation based on few parameters. The adjustment of these parameters on the settlements observed ahead of the tunnel face leads generally to a quite accurate prediction of the settlement evolution with the tunnel progress and in particular its final stabilized value. This permits to continuously adapt the tunnelling process in order to avoid building damage and to optimize economically the pre-reinforcement.

Firstly, the principal characteristics of the South Toulon tunnel will be presented. Then, the study will focus on the method used to analyze and predict the ground displacements in order to optimize the tunnel progress. Some examples of this approach will be described as well.

2 SOUTH TOULON TUNNEL

The South Toulon tunnel will connect motorways A50 and A57 from Nice to Marseille (Fig. 1). It is parallel to the North tunnel previously built between 1994 and 2000. It has a 120 m^2 section and is 1820 m long. It is realized in an urban area with a limited overburden (about 35 m maximum). The tunnel construction presents many difficulties starting from the characteristics of crossed soils.

2.1 *Geology and geotechnical context*

One of the most important difficulties of this project is the Toulon geology. In fact, it is very heterogeneous at the tunnel face scale (Fig. 2) and

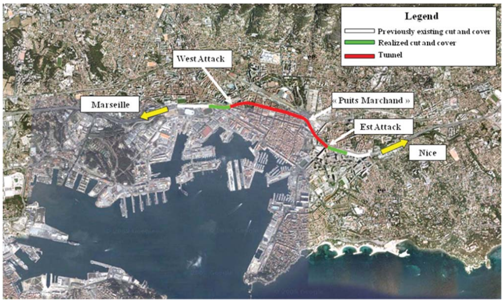

Figure 1. South Toulon tunnel location.

Figure 2. A South Toulon tunnel face.

along the tunnel layout. Thus, several geological and geotechnical investigations (sample and destructive drillings, pressuremeter tests ...) were performed. Such studies identified more than ten different soil types: altered and fractured quartzophyllites, Permian claystone, Gypsum, Trias limestone, Breccia, etc. Besides, the geological formations are often characterized by a thrust phenomenon.

Due to the geological heterogeneity and to the difficulty to make tests on undisturbed samples, the geotechnical model is not easy to define. For instance, for the quartzophyllites, only the Young modulus could be found from a statistic analysis of the pressuremeter tests. A value of 120 MPa is used in the preliminary project.

As a consequence of this high geological incertitude, horizontal drillings are done from the tunnel face during the tunnel progress as well. In addition, the geologists control and analyse the tunnel face after each excavation step before shotcreting.

2.2 *Excavation method*

Because of the high geology variation and in order to control the surface settlements, the ground mass ahead of the tunnel face was reinforced by a pipe umbrella and face bolting with different densities. Figure 3 shows one of the most common reinforcement profile used in the project. The Table 1 summarises the principle characteristics of reinforcement bolts (average values). In fact, density, length and renewal vary continuously depending on soil conditions and settlements previsions.

Face Bolts Fibre glass/Steel 18 0 4.5/9.

The excavation progresses generally by 1.5 m steps. After each step, one HEB 180 rib is installed and the unsupported soil is lined with shotcrete.

The tunnel invert (HEB 220) is realized either immediately or with a delay depending on ground deformations.

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 allows realizing full face excavations of tunnels even under difficult ground conditions. This methodology permits to increase tunnel stability and to reduce tunnel deformations and surface settlements in case of shallow tunnels.

In Lunardi's theory, the function of the prereinforcements ahead of the face is to prevent the loosening of the soil and is defined as "conservation" interventions. He describes two mechanisms of "conservation":

- Protective conservation: the reinforcements have to channel the stresses around the advance core in order to maintain the natural strength and deformation characteristics. In the case of Toulon tunnel, this role is played by the pipe umbrella.
- Reinforcement conservation: the reinforcements improve directly the natural strength and stiffness of ground in the core ahead of the tunnel face. Horizontal fibre-glass bolts are used for

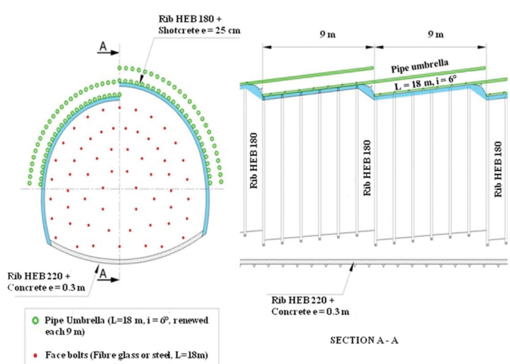

Figure 3. A common reinforcement profile of South Toulon tunnel.

Table 1. Reinforcement characteristics.

Reinforcement type	Material	Length (m)	Inclination (°)	Renewal (m)
Pipe umbrella	Steel	18	6/14	9
Face bolts	Fibre glass/steel	18	0	4.5/9

this purpose and they are one of the keys to the success of this technology. In fact they present high axial strength but they can be cut easily during the excavation.

The "ADECO-RS" approach can be summarized in two steps: a design stage and a construction one. The first phase consists in a geological and geotechnical analysis of the ground through which the tunnel passes and in the tunnel division into sections with uniform stress-strain behaviour. For each section, thresholds levels of deformations can be chosen depending mainly on the overburden, the geology and the buildings resistance, which are previously investigated. Then, considering such previsions, the type of reinforcement to apply has to be chosen. In the second step (the construction stage) stabilization works are set up based on design predictions. During the following phase, the continuous monitoring of the displacements in the tunnel and at the ground surface is essential (see Fig. 4).

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

In the last twenty years, several examples have proved the validity of this approach: Rome-Florence rail line (1985), San Vitale tunnel (Italy, 1991), Tartaiguille tunnel in TGV rail line (France, 1998).

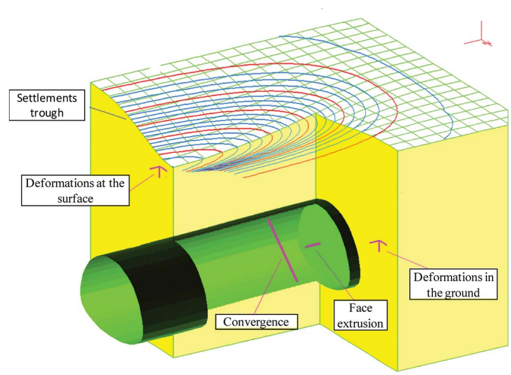

Figure 4. Ground deformations and surface settlements during the excavation of a shallow tunnel.

2.3 *Automatic system for settlement measurements*

Because of the complexity of the Toulon geology and the high urbanization above the tunnel layout, an automatic system of settlement measurements has been set up by SOLDATA. These measures are added to a regular control of tunnel displacements (convergence and face extrusion).

The principal objectives of such monitoring are the followings:

– to guarantee the short term tunnel stability and therefore the workers security;
– to verify the impact of excavation on buildings and to avoid damage;
– 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 displacements with a high frequency. A transverse profile is defined every 9 m along the whole tunnel layout. There are two different approaches (see Fig. 5). In order to measure the ground settlement, the automatic stations record the vertical movement of points positioned on a virtual horizontal grid without the need for targets. Thanks to these measures, the ground subsidence profiles can be plotted and the differential settlements, which cause the building structure damages, can be calculated. These data are collected once per day (CENTAURE system). The same stations can point at prism targets, fixed on buildings, and they record their movements in X, Y, Z directions. In this case the measure is recorded every two hours (CYCLOPE system). Table 2 summarises the different characteristics of the two measurement systems.

In order to avoid systematic errors, the total stations are regularly calibrated against prism targets considered fixed because far from the influence zone of excavation progress.

All data are immediately centralized in a geographical information system and recorded in a pc database. The database contains also tunnel displacements measures and other important information, such as geological tunnel face surveys, piezometric measurements and tunnel work timing.

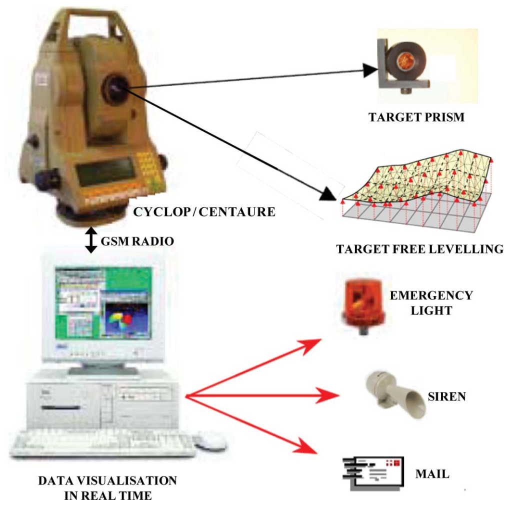

Figure 5. CYCLOP and CENTAURE measurement systems (SOLDATA).

Table 2. Characteristics of the automatic measurement systems.

System	Measure directions	Frequency	Precision
CENTAURE	Z	1 measure/ day	+/– 0.5 mm
CYCLOP	X, Y, Z	1 measure/ 2 hours	+/– 0.5 mm

Thanks to a remote access, the project team can connect onto the site and observe the monitored data from their offices. Moreover, in order to facilitate the analysis of the measured movements, automatic curves are generated and available on the webpage. As far as the works security is concerned, 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 is based mainly on the prevision of surface settlements development on the tunnel axis. The following section describes such methodology.

3 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, this analysis is regularly made, especially when the excavation concerns an urbanized zone. Nevertheless, the prereinforcement and lining adjustment 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 formulation describing the development of surface settlements on the tunnel axis with accuracy.

3.1 *Models describing the settlements on the tunnel axis*

Figure 6 shows the settlements of three surface points directly above the tunnel axis against their distance from the tunnel face. The curves were done when the tunnel face was located at chainage PM 1081. The surface point PM 1095 is, in this example, 14 m ahead of the tunnel face and it settles down by 10 mm already. The point PM 1075 is 6 m behind the tunnel face with 25 mm of settlement. Finally, the movement of the point PM 1018, 63 m behind the tunnel face, is stabilized. The graph shows that more than 40% of surface displacements can take place ahead of the tunnel face. The curves evolve thanks to the new measures arriving with the tunnel face progress.

In order to make settlement previsions, it is necessary to find an equation that is able to describe the developments of surface settlements on the tunnel axis. Afterwards, the prediction method consists in calibrating the parameters of the model on the first settlements observed ahead of the tunnel face. This optimization can be repeated each time new data are collected. The final settlement prevision becomes therefore more and more accurate with the tunnel progress.

A normal exponential equation was used in some tunnel construction sites in order to describe the trend of settlements along the tunnel axis.

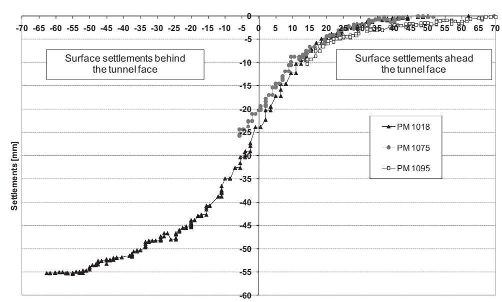

Figure 6. Settlements of three surface points caused by the excavation advancement.

Grasso & Pelizza (1994) analysed the settlements measured during the construction of Doria tunnel, in the Voltri railway layout. They concluded that it is possible to represent the settlements evolution against the distance from the tunnel face with an exponential equation depending on the tunnel overburden.

Dubois & Jassionnesse (1997) analysed the in-situ measurements of North Toulon excavation. Based on the Sagaseta (1987) method, they suggested that the settlement of a surface point, caused by the excavation of a section of the tunnel (source), is proportionally controlled by the displacements at the source and inversely proportional to the square of the distance between the point and the source.

Serratice & Magnan (2002) studied the settlements evolution (S) against the distance from the point considered to the tunnel face (x) in a section of the North Toulon tunnel. Starting from the Loganathan & Poulos (1998) approach, they proposed the following semi-empirical equations:

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

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

with

$$A = \frac{a \cdot H^2}{\left(R + H\right)^2}, \quad X^2 = \frac{\left(x - x_0\right)^2}{H^2} \tag{3, 4}$$

In the previous equations, x_0 is the distance of the point at ground surface ahead of the tunnel face where the settlements start to appear. S_0 is the maximum settlement expected and R and H are respectively the tunnel radius and the tunnel depth. Finally, they calibrated the a parameter ($a = 0.25$). This model has the advantage to have only two unknown parameters, S_0 and x_0.

Bourgeois (2002) carried out three dimensional finite element analyses using the CESAR-LCPC code to simulate the North Toulon tunnel excavation. The following equations were suggested in order to represent the numerical results:

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

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

with

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

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

The Serratrice-Magnan and Bourgeois models were tested on the settlements trend on the tunnel axis, measured during the South Toulon tunnel excavation (see Fig. 7).

Nevertheless, another model is analysed as well. It is an empirical model based on the optimisation of exponential equations on in situ settlements measured in different projects, such as the Jubilée Line in London. The equation is the following (8):

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

where

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

In order to obtain a better approximation with the South Toulon data, the previous expression is modified, introducing an additional parameter a. It is a translational parameter that permits to modify 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 on stabilized points

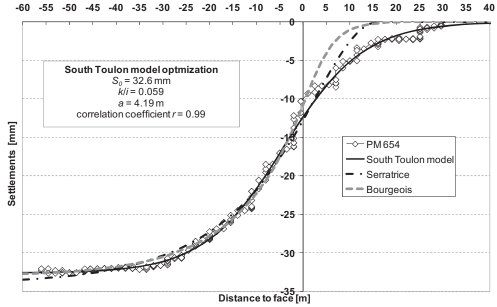

Figure 7. Optimization of three models on an example of South Toulon tunnel in situ settlement measurements.

shows that the modified approach proposed in Eq. 9 gives the best results in the particular case of the South Toulon tunnel. Therefore, it has been chosen to make the final settlement predictions.

In fact, as shown in the example on Figure 7, with both Serratrice-Magnan and Bourgeois models, it is possible to obtain a good approximation of the settlements progression behind the tunnel face ($x < 0$). Nevertheless, they are not able to represent the settlements ahead of the tunnel face ($x > 0$). On the other hand, the modified approach leads to a rather accurate estimation of the whole settlement evolution with the tunnel advance, by an adjustment of the 3 free parameters (S_0, ratio k/i and a) on the settlements observed ahead the tunnel face (Fig. 7).

3.2 *South Toulon tunnel settlement thresholds*

In the South Toulon tunnel project, the tunnel layout is divided in different sectors, each one characterized by three threshold levels (vigilance, anomaly and alert). These thresholds are related to the final absolute and differential surface settlements and depend mainly on the overburden, the geology and the buildings resistance.

In addition to the settlements predictions, the modified approach is also used, for each sector, to draw the three curves corresponding to the three settlement thresholds. 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 sector concerned.

The real time comparison of the predicted settlement curves with the 3 threshold curves corresponding to the sector is the basic element of the adjustment of tunnel process.

In fact, the project contract imposes the following conditions:

– if the settlement prediction curves are above the vigilance threshold one, a reduction of the prereinforcement is recommended;
– if the settlement previsions exceed the anomaly curve and come close to the alert one, it is necessary to change the tunnel process, increasing for instance the prereinforcement, in order to limit further settlements and stay close to the anomaly threshold.

In order to economically optimize the works progress and, at the same time, to avoid building damages, the tunneling process has to be continuously adapted fitting the settlement evolutions on the anomaly curve. An example of this approach is presented in the following section.

3.3 *Example of tunneling process adaptation on settlements prediction*

Figure 8 shows the study on the settlements evolutions of a Toulon sector realized when the tunnel face was at point of advancement (PM) 820. This zone is characterized by the quartzophyllites.

The points at PM 766, 782, 802 started their settlement ($x > 0$) with a worrying trends next to the alert curve.

Besides, during the excavation from the PM 758 to PM 792, tunnel face instabilities often occurred. For all these reasons, in accordance with the project contract, the following modifications of the tunneling process were applied:

– the umbrella pipes were increased from 21 to 33 unit and their inclination moved from 14° to 6°;
– the face bolting was improved with 15 short autodrilling bolts, 9 m of length, grouted with resin;
– the face tunnel excavation was divided in 5 different steps in order to limit the instabilities.

These operations permitted to decrease the face tunnel instabilities but also to ameliorate the surface settlements evolution. In fact, the settlements trends of the analyzed points (PM 766, 782, 802) returned, in the left part of the graph, toward an acceptable tendency between the vigilance and anomaly thresholds curves.

After having passed this critical zone, the ground conditions improved. The settlements trends of the points above and ahead the tunnel face (PM 811, PM 818 and PM 829) ameliorated as well. As shown in the Figure 8, the prediction curve for these points, done when the tunnel face was at PM 820, led to a final settlement above the vigilance threshold. Therefore, the team project decided to modify once more the tunneling process in order to economically optimize the prereinforcement. The umbrella pipes were substituted with autodrilling bolts having a smaller inertia. In addition, the

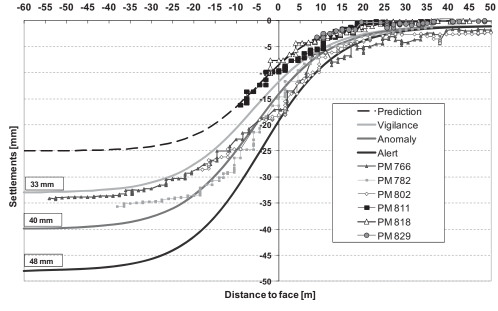

Figure 8. Example of tunnelling process adaptation on settlements predictions.

face bolting was lightened and the rib invert was suppressed.

3.4 *Surface settlements analysis in the transverse sections*

During the South Toulon tunnel excavation, in addition to the analysis of settlement evolution at ground surface directly above the tunnel axis, the trends of the surface subsidence in transverse sections have also been considered. Numerous studies (Peck 1969, Schmidt 1969, Attewell & Farmer 1974, Atkinson & Potts 1977, etc.) 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}: maximum ground surface settlement above the tunnel axis;
x: horizontal distance to the tunnel axis;
i: 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. The i value identifies the area in which the settlements curve presents a curvature change and the slope (β) of the subsidence profile is maximum. Besides, it separates two zone of the soil: 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. The researches of Skepmton & MacDonald (1956), based on the observation of 98 buildings, showed that, to induce damage in the concrete structures, it is necessary to reach a value of β equal to 1/150. More cautious allowable values are proposed in Eurocode 7: β equal to 1/500 for framed structures in reinforced plugged concrete and 1/200 for open frames. These values were suggested by Polschin & Tokar (1957).

Figure 9 shows the example of the analysis of the movements measured in the Chalucet street, perpendicular to the Toulon tunnel axis. This zone is characterized by the quartzophyllites. The two different monitoring systems were available in this street. There were ground surface points on the street (CENTAURE) and targets points installed on the buildings (CYCLOP).

The optimization with the least squares method of the parameters of Peck's approach for the

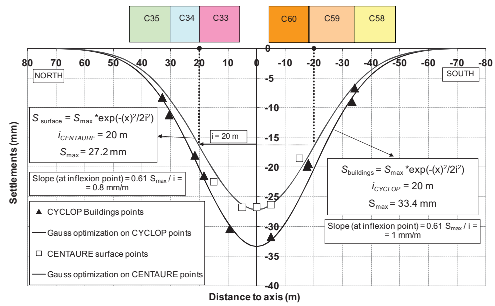

Figure 9. Gauss optimizations on transversal settlement measures.

transverse trough has been conducted on both sets of values. In the Figure 9, the different buildings (C35, C60, etc...) are also shown with their respective positions relative to the tunnel axis. In both cases, the values of i are the same. With this value, it is possible to locate the two points of inflection of the settlement trough and compare them with the buildings position. The result is that, in the given example, the most critical consequences could appear at the contact between buildings C34 and C33 on the north side and between C60 and C59 on the south side of the tunnel layout. Nevertheless, in this case the maximum slope at inflexion point was low (1 mm/m) and no damage appeared in the buildings.

Even if the buildings seem to follow the ground subsidence profile, the two optimizations diverge when getting close to the tunnel axis. The absolute settlements measured on the buildings are larger than those observed on the ground surface. This gap increases especially after the inflexion point. This phenomenon is probably caused by the weight and the low stiffness of the buildings.

3.5 *Differential settlements predictions*

As shown in the previous paragraph, it is essential to study the development of both differential and absolute settlements in order to avoid buildings damage. The differential settlement of a building is the ratio between the settlements difference of two target prisms fixed on its structure and the horizontal distance between them. The building size and position with respect to the settlement profile and its structure characteristics determine its differential settlement. As for absolute settlements, the project contract imposes three threshold levels of final differential settlements for each sector of Toulon layout. Therefore, it was necessary to elaborate a prediction method for this kind of settlements, as well.

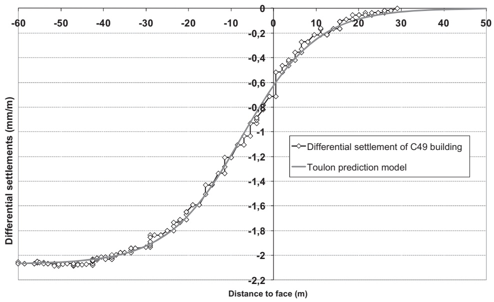

Figure 10. Model prediction of differential settlements.

The proposed approach for the prevision of absolute settlements on Toulon tunnel axis was tested on the differential settlements. The study revealed that it is possible to use the same model for the absolute settlements prediction.

As shown in the example below (Fig. 10), it is satisfying to substitute S_0 with the maximum predicted differential settlement ($S_{diff\ max}$) in the equation (9). The prevision method is the same of this for absolute settlements. The model is adapted on the first differential settlement observed ahead of the tunnel face. It is eventually optimized as soon as new measures are obtained. The final differential settlement prevision, 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 fulfil the project contract conditions.

4 CONCLUSION

During the excavation of urban deep tunnels, it is essential to control and reduce the settlements in order to avoid buildings damage. This paper proposes a method of settlements prediction based on a simple analytical equation. This equation has been validated by analysing the surface settlement caused by the excavation of the South Toulon Tunnel. The examples shown in this study prove that this model can be applied to both absolute and differential settlement previsions. The proposed equation proved to be a useful tool for the observational method during tunnel excavation. In fact, through this model, it is possible to continuously adjust the tunnelling process just by comparing the predicted settlements to the threshold values imposed by the project contract.

It could be interesting to test this equation on other tunnel projects in order to validate it. Besides, this could permit to find a relation between the model parameters (k/i and a) and the project features, such as the soil and the prereinforcement characteristics.

REFERENCES

Atkinson, J.H. & Potts D.M.1977. Subsidence above Shallow Tunnels. *Journal of Geotechnical Engineering,* Vol. 103: 307–325.

Attewell, P.B & Farmer I.W. 1974. Ground deformation resulting from shield tunnelling in London clay. *Canadian Geotechnical Journal*, Vol. 11: 380–396.

Bourgeois, E. 2002. Analyse numérique tridimensionnelle des tassements provoqués par le creusement d'un tunnel par la technique du prédécoupage mécanique – Application à la traversée souterraine de Toulon. *Bulletin des laboratoires des Ponts et Chaussées,* Vol. 237: 37–57.

Dubois, P. & Jassionnesse, C. 1997. The Toulon underground tunnel crossing. First feedback analysis carried out using on-site measurements. *Tunnel for people, Conference of the International Tunneling Association:* 157–162.

Grasso, P., Brino, L., Rabajoli, G., Astore, G., Pelizza, S. 1994. Metodologia per la previsione ed il controllo delle subsidenze. Un'applicazione: La Bretella di Voltri. *Gallerie e grandi opere sotterranee*, Vol. 43: 12–25.

Loganathan, N. & Poulos, H.G. 1998. Analytical prediction for tunnelling-induced ground movements in clays. *J. Geotech. Geoenviron. Eng.*, Vol. 124(9): 846–856.

Lunardi, P. (ed) 2008. Design and construction of tunnels–Analysis of controlled deformation in rocks and soils (ADECO-RS). Berlin: Springer.

Peck, R.B. 1969. Deep excavation and tunnelling in soft ground. *7th ICSMFE State of the art Volume:* 225–290.

Polschin, D.E. & Tokar, R.A. 1957. Maximum allowable non uniform settlements of structure. *Proc 4th Int. Conf. on Soil Mech. and Found.*, Vol 1: 402–405.

Sagaseta, C. 1987. Evaluation of surface movements above tunnels. A new approach. *Colloque Interaction Sols Structures:* 445–452.

Schmidt, B. 1969. Settlements and ground movements associated with tunneling in soil. *PhD thesis.* University of Illinois.

Serratrice, J.F. & Magnan, J.P. 2002. Analyse des tassements de surface pendant le creusement du tunnel nord de la traversée Souterraine de Toulon, *Bulletin des laboratoires des Ponts et Chaussées,* Vol. 237: 5–36.

Skempton, A.W. & MacDonald, D.H. 1956. Allowable settlement of buildings. *Proc. of Institute of Civil Engineering*, Part III, Vol. 5: 727–768.