Ground movement control in the construction of a new metro line in Barcelona

A. Gens, A. Di Mariano, J.M. Gesto
Departamento de Ingeniería del Terreno, Technical University of Catalunya, Barcelona, Spain

H. Schwarz
GISA, Josep Tarradellas 20–30, Barcelona, Spain

ABSTRACT: Ground movement control is of paramount importance in the construction of a new Metro line in Barcelona given the large diameter of the excavation and the need to cross heavily built areas. A variety of construction procedures for ground movement control are envisaged. In the paper three examples from the early part of the project are described. They involve: (i) the installation of a screen of jet grouted columns, (ii) compensation grouting, and (iii) structural jacking.

1 INTRODUCTION

A large tunnelling project is under way in Barcelona involving more than 40 km underground excavation (Schwarz et al., 2005). The special design of this new Metro line (Line 9) requires the use of large diameter (12 m) Tunnel Boring Machines (TBMs). The parts of the city crossed by the line are heavily built without a systematic street pattern. Therefore, a large proportion of the tunnels underlies directly or is very near existing buildings. The issue of ground movement control is, therefore, of paramount importance. Although, wherever possible, the ground cover is considerable, the large diameter of the tunnel still implies potential movements that can be quite significant.

There are a number of construction procedures that can be used to try to control and minimize the movements of structures affected by tunnelling (Harris, 2001). In recent years, compensation grouting (Mair & Hight, 1994) has been a widely used method using both fracture grouting (e.g. Harris et al., 1999; Osborne et al., 1997, Pototschnik (1992), Schweiger & Falk, 1998, Standing et al., 2001) and, less frequently, compaction grouting (e.g. Graf, 1992, Ziegler & Wirth, 1982). When the potentially affected structures lie to the side of the tunnel, another possibility is to insert a structural element between the excavation and the building. This limits the size of the settlement trough beyond the structural element. This element may be a diaphragm wall or piles. Jet grouted columns, however, provide an interesting alternative (Oteo et al., 1999) because of a higher flexibility of installation, allowing for instance, the use of inclined elements. Surface occupation is also normally more limited.

In the construction of Line 9, it is envisaged to resort extensively to compensation grouting and insertion of structural elements (piles and jet grouted columns) in the areas where significant movements are expected. Other alternative methods may also be used for specific problems.

In this paper, three examples of ground control movement carried out during the early part of the project construction are described. They involve the use of jet grouted columns, compensation grouting and structural jacking.

2 GROUND MOVEMENT CONTROL USING JET GROUTED COLUMNS

2.1 *Description of the treatment*

In Salvador Seguí street, tunnelling alignment was close to a number of multi-storey residential buildings. Tunnelling, using an EPB machine, was performed in a Miocene conglomerate consisting of a stiff clay matrix containing boulders. Above this layer there appears a stratum of sandy silt with gravel of Quaternary origin with SPT values in the range 15–25. The ground cover is about 25 m so that the cover/diameter ratio (C/D) is approximately 2. Figure 1 shows a typical cross section.

Although the expected movements during tunnelling in this Miocene material were expected to be low, the possible effect of the Quaternary materials above and the presence of multi-storey buildings caused some concerns, especially considering that this was the first potentially damageable zone reached by

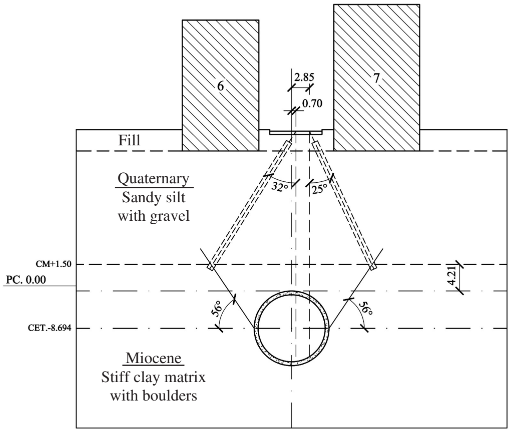

Figure 1. Ground movement control by means of jet grout columns. Typical cross section.

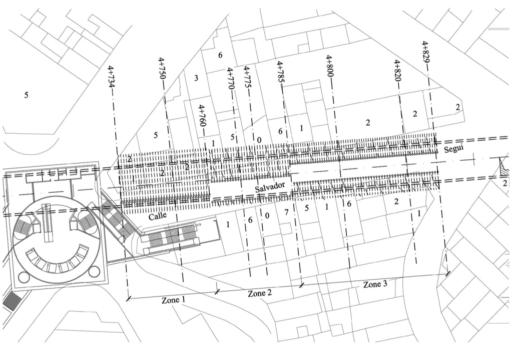

Figure 2. Ground movement control by means of jet grout columns. Plan view.

the excavation of the line. As a consequence, it was decided to install a screen of jet grouting columns between the tunnel and the buildings. As Figure 1 shows, the jet grouted columns were inclined and were designed to reach the Miocene layer. The columns were formed using the single fluid method and achieved a diameter of 60–70 cm. In plan, their axes were separated 1.2 m. Figure 2 shows the layout of the ground treatment. It can be observed that the position of the columns is easily adapted to the various relative positions of tunnels and buildings.

2.2 *Ground movement observations*

Figure 3 shows the surface settlements measured at a cross section at chainage, PK 4+800. The movements recorded after the jet grouting operations, the settlements caused by the tunnelling and the final vertical displacements are shown. It can be seen that jet grouting caused some significant heave movements reaching a maximum of 10 mm above the axis

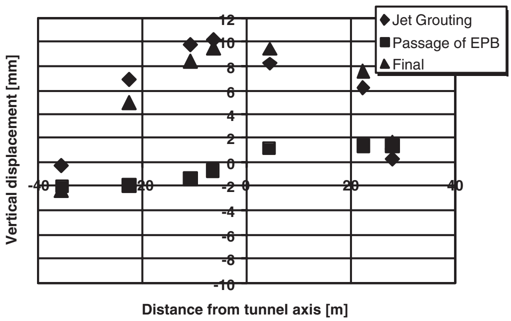

Figure 3. Observed settlements in section PK 4+800 for various construction stages.

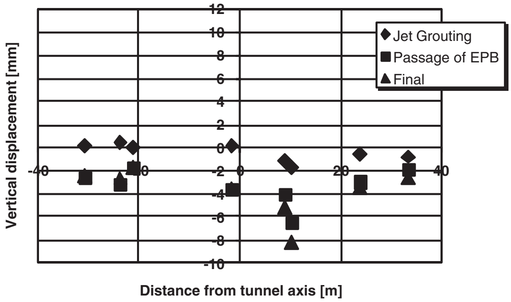

Figure 4. Observed settlements in section PK 4+770 for various construction stages.

of the tunnel. Heave movements were detected in the buildings as well. In contrast, the movements due to tunnelling itself were quite small; therefore, the final settlements were quite close to those caused by the installation of the jet grout columns.

To correct this effect, the jet grouting technique was modified, avoiding the treatment of shallow ground and improving spoil removal. As Figure 4 shows (chainage PK 4+770), the movements caused by jet grouting were then small, and the final settlements were almost exclusively due to the construction of the tunnel.

2.3 *Modelling*

The ground movements at depth were observed at the section at chainage PK 4+750 that was equipped with an inclinometer and an extensometer, as shown in Figure 5. Those observations provided an opportunity to perform a first calibration of a numerical model to represent, in an approximate way, the ground response to tunnelling. Consequently, only the movements due to the tunnel construction have been considered. The various soil layers were modelled with a Mohr Coulomb elastoplastic model. The same model, with higher stiffness and cohesion, was used for the jet

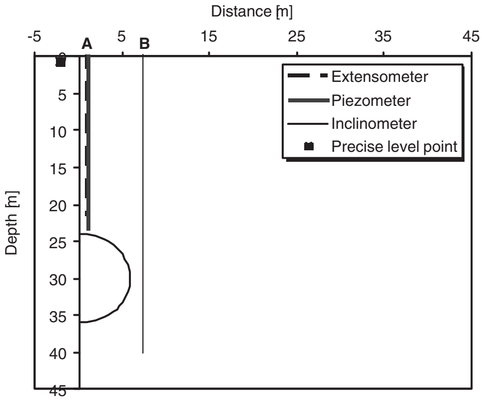

Figure 5. Instrumented section at chainage PK 4+775.

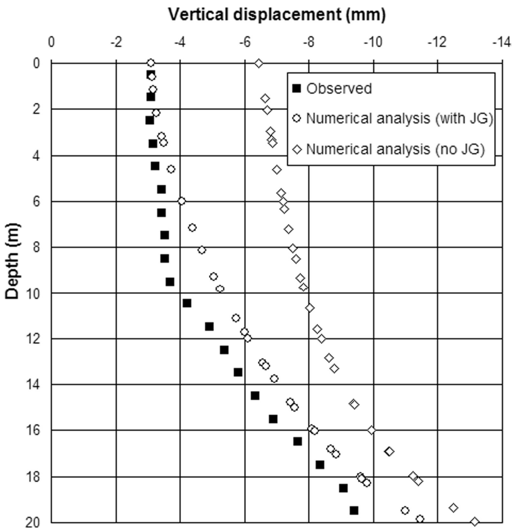

Figure 6. Observed and computed vertical displacements at section PK 4+775.

grout columns. A very small tensile strength was specified for those columns. The convergence-confinement method (Panet & Guenot, 1982; Kielbassa & Dudeck, 1991; Potts & Zdravkovic, 2001) was used to represent three dimensional tunnelling effects. To achieve the desired amount of ground loss, it was assumed that stresses had been reduced by a factor of 0.63 at the time that lining was installed.

Figures 6 and 7 show that it is possible to reproduce reasonably accurately the observed extensometer and inclinometer readings, except for the horizontal movements close to the surface. Accepting that, after calibration, the numerical model represents approximately the real system, it is possible to evaluate the beneficial effects of the jet grout columns by running an analysis without them. The results of the analysis

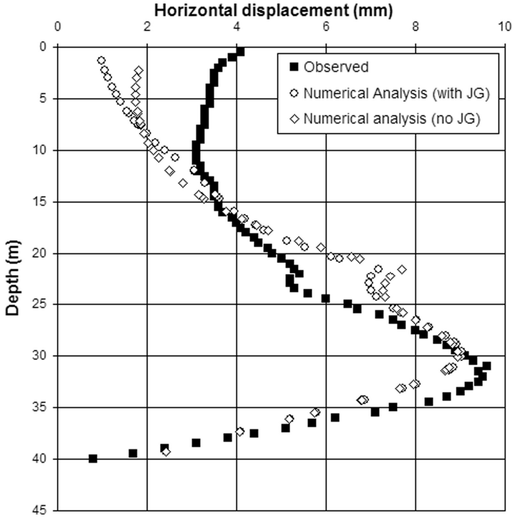

Figure 7. Observed and computed horizontal displacements at section PK 4+775.

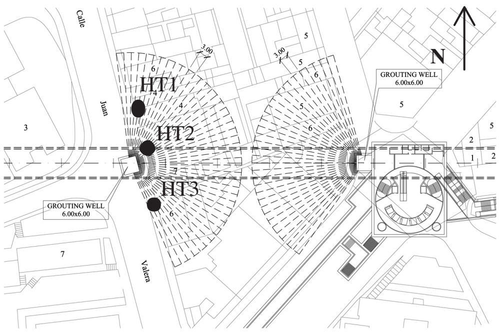

Figure 8. Compensation grouting performed at the Juan Valera road zone. Plan view.

without jet grout columns (shown also in Figures 6 and 7) suggest that they are effective in reducing settlements, especially close to the surface. The volume of the settlement trough is 0.27% with jet grout columns and 0.35% without. In contrast the effect on horizontal movements is minimal.

3 COMPENSATION GROUTING

In the zone close to Juan Valera road, the tunnel was located directly below a group of residential buildings. The ground cover was similar to the previous one (about 25 m) but now, excavation took place wholly in the Quaternary detritic material. To minimize ground movements compensation grouting was undertaken. Figures 8 and 9 show a plan view and a cross section of the ground treatment performed.

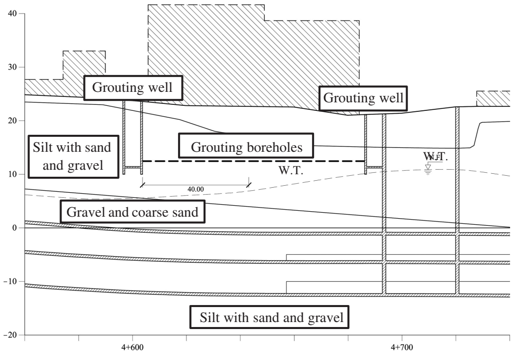

Figure 9. Compensation grouting performed at the Juan Valera road zone. Cross section.

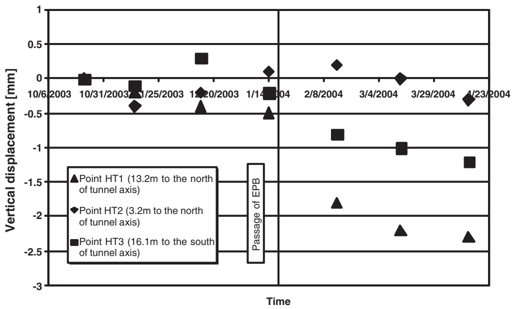

Figure 10. Evolution of vertical settlements in zone treated with compensation grouting.

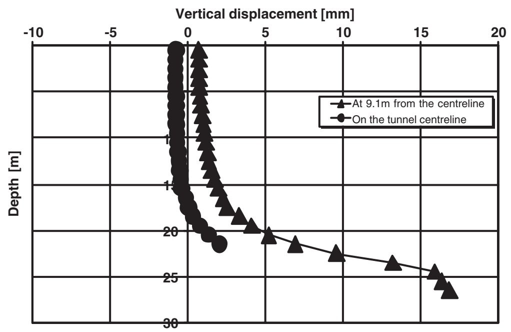

Figure 11. Distribution of vertical settlements measured in two extensometers after tunnelling and compensation grouting.

Two square vertical wells ($6 \times 6\,m^2$) were excavated in the locations shown in Figures 8 and 9. Boreholes were drilled from them that were subsequently equipped with "tubes-a-manchettes". The maximum length of the boreholes was 40 m. For movement compensation, fracture grouting was used. Figure 10 shows a typical evolution of surface settlements in this zone. It can be observed that vertical displacements at the surface were kept quite small, below 2.5 mm. More information is given in Figure 11 where the final distributions of settlements with depth measured in two extensometers are plotted. One of the extensometers is located on the centreline and the other one at about 9 m away from it. It can be seen that, although the vertical displacement of the crown of the tunnel is about 25 mm, the settlements reaching the surface are actually very small. In fact a small heave (1 mm) remains at the end in one of the extensometers.

4 STRUCTURAL JACKING

A critical point of the first part of tunnelling operations was the crossing of the Ronda Litoral, a main urban motorway that carries a significant part of the city traffic (Figure 12). Note that the crossing is not perpendicular to the motorway axis. The motorway runs alongside the Besos river and is founded on the river alluvium. The cross section (Figure 13) shows that now the ground cover is lower, about 12–14 m (C/D = 1 approx.). Tunnelling is in the soft alluvium, composed of sands, gravels and, occasionally, lower permeability silts. The water table is controlled by the river level and it is close to the surface. Tunnelling conditions are therefore more severe.

To control ground movements, structural jacking was preferred instead of compensation grouting. The reason was that the structure was very accessible and it was felt that, since the main goal was the preservation of the structure, acting directly on it provided a more immediate and efficient control method. Compensation grouting, in contrast, would only affect the structure through ground movements, a more uncertain proposition. The required vertical displacements were imparted by pairs of hydraulic jacks inserted between the piers and the deck (Figure 14).

The motorway structure was intensely monitored with continuous readings during the period of tunnel crossing. When vertical movements reached a trigger level (usually 5 mm), jacks were operated to compensate the settlement. A previous structural analysis had determined the maximum allowable differential settlement between adjacent piers.

As an additional precautionary measure, two micropile screens were installed between the tunnels and the motorway. The main objective was to minimize the risk of localized failures in case of machine malfunctioning or other unforeseen tunneling difficulties. The micropiles had lengths of 32 m and 41 m (depending on the side from which they were drilled) and a diameter of 114 mm. The drilling tube was left in place as micropile steel reinforcement. The micropiles were grouted after installation.

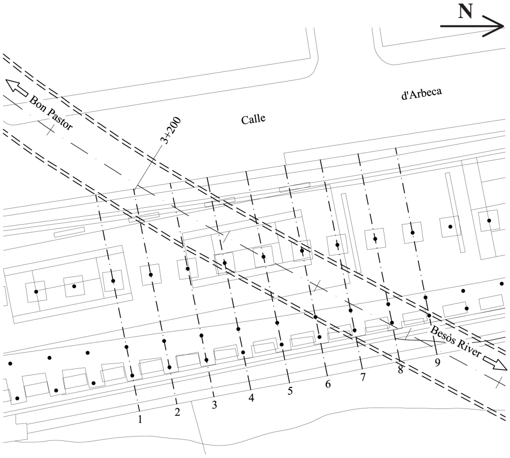

Figure 12. Plan view of the crossing of the motorway by tunnel construction.

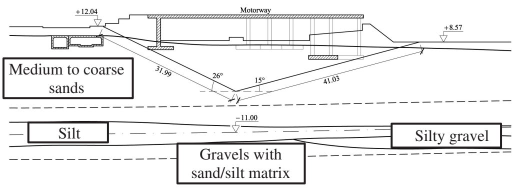

Figure 13. Crossing of the motorway by tunnel construction. Cross-section.

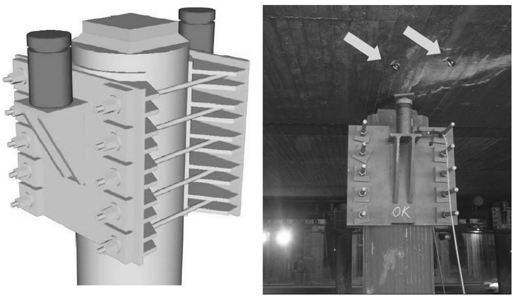

Figure 14. Scheme and photograph of hydraulic jacks used for compensating ground movements. The levelling points to measure deck movements are indicated.

In Figures 15 and 16, the vertical ground movements at the surface below the motorway structure have been plotted. It can be seen that the movements are now significant, with volume losses of 1.1% and 0.7% respectively. These large ground losses reflect the type of material that is being tunnelled (alluvium below a high water table), softer and more compressible than the ground encountered before. It can also be observed that, at least in one case (Figure 16), micropile installation resulted in a noticeable heave.

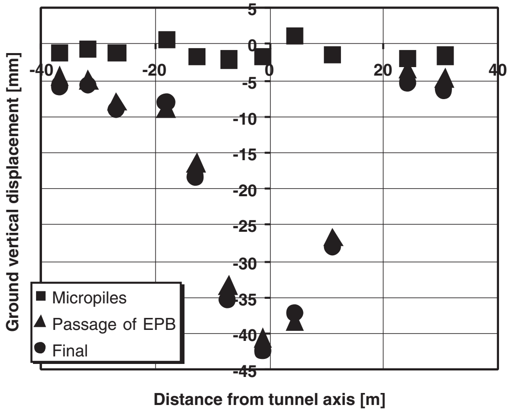

Figure 15. Distribution of surface settlements in a cross-section below the central piers of the motorway structure.

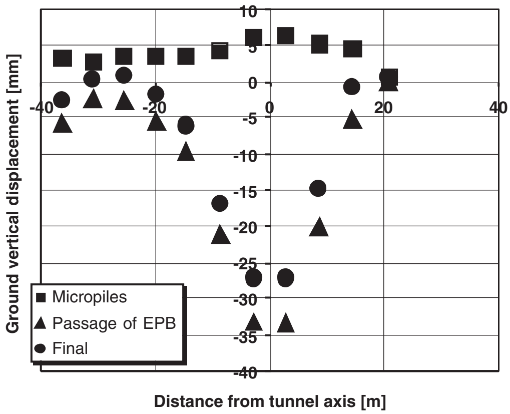

Figure 16. Distribution of surface settlements in a cross-section below the perimeter wall of the motorway structure.

The effectiveness of the structural jacking can be assessed by reference to Figures 17 and 18. They show the evolution of settlements of two points on the structure. For comparison, the corresponding movements of the ground surface are also shown. The differences between the two curves are due to the effects of structural jacking. It can be observed that the movements of the structure have been kept limited. For completeness, the movements observed during micropile installation are also plotted in the figures. Finally Figure 19 shows a detail of the variation of settlement of a point on the structure focused on the jacking period. The jacking operations can be identified. It should be pointed out that, in the structural jacking process, the prevailing restriction was not based on absolute movements but on the differential movements between the various parts of the structure.

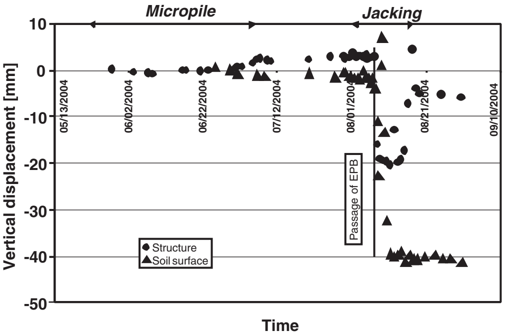

Figure 17. Evolution of settlements of a point located on the central piers of the motorway structure. The settlements of a corresponding point on the ground surface are also shown for comparison.

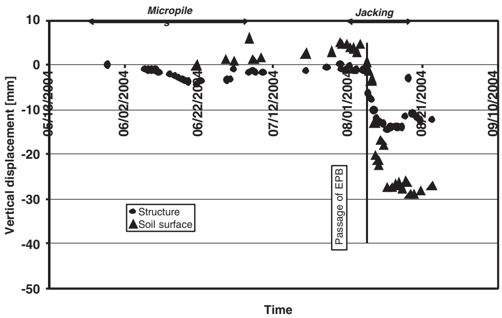

Figure 18. Evolution of settlements of a point located on the perimeter wall of the motorway structure. The settlements of a corresponding point on the ground surface are also shown for comparison.

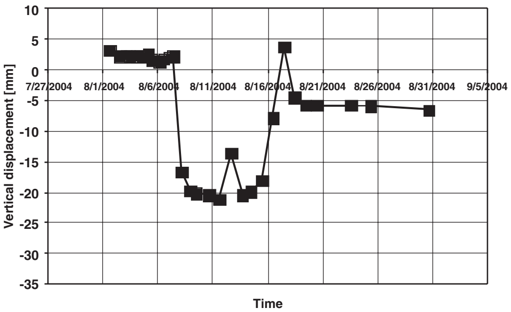

Figure 19. Evolution of settlements during the jacking period of a point located on the central piers of the motorway structure and 6 m south of the tunnel axis.

5 CONCLUSIONS

There is a wide range of techniques to limit ground movements caused by tunnelling operations. The selection of a particular one is very much dependent on the specific features of the site, location of the structures in relation to the tunnel, accessibility and ground conditions. Three examples derived from the initial stages of construction of a new Metro line in Barcelona, involving different techniques, have been described. In general, they have achieved their intended goal. It should always be considered that any type of protective measure may give rise to ground movements by itself. It is necessary, therefore, to apply them very carefully, in order to maximize their efficiency and to minimize possible unwanted effects.

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