Compensation Grouting with shallow and deep foundations – case study from the Metro B1 in Rome

Injections de compensation pour les fondations superficielles et profondes – étude de cas de la ligne de métro B1 à Rome

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ABSTRACT: For the construction of the new Metro B1 line in Rome a large number of geotechnical specialist works were performed for the considerably deep stations and the protection of buildings. In two areas where the cover between the foundation and the tunnel was very limited (less than 3 m distance), compensation grouting was utilized to mitigate TBM induced settlements for structures founded on shallow and deep foundations with 19 m long piles, respectively. The paper presents the experience of the two compensation grouting works, discussing the problems associated with the shaft construction and addressing the results of full-scale field trials made in order to study the efficiency of compensation grouting.

RÉSUMÉ : Pour la construction de la nouvelle ligne de métro B1 à Rome, un grand nombre d'ouvrages spécialisés géotechniques a été effectué pour le bâtiment considérablement profond de la station, ainsi que pour la protection des bâtiments. Dans deux secteurs, où la distance entre la fondation et le tunnel a été très limité (moins de 3m), des injections de compensation ont été utilisés pour atténuer les affaissements de bâtiments induits par le tunnelier pour des structures fondées respectivement sur des fondations superficielles ou profondes avec piles de 19 m de longueur. Cet article présente l'expérience des deux ouvrages avec des injections de compensation, en discutant les problèmes liés à la construction du puits et en traitant les résultats des essais à grande échelle complets, réalisés afin d'étudier l'efficacité des injections de compensation.

KEYWORDS: Compensation grouting, deep shafts, infrastructure works, urban tunnelling

1 INTRODUCTION

The new underground lines Metro B1 and Metro C are important infrastructure works for Italy's capital city Rome. Both Metro lines are characterized by challenging construction conditions due to varying ground properties, deep stations with high groundwater table and archaeological records. In particular, the realization of the Metro B1 as a branch of the existing line Metro B was difficult with its 4 new stations and the excavation of approx. 7 km single track tunnel with 6.8 m diameter and 1 km of double track tunnel with 9.8 m diameter. The construction started in 2005, and tunnelling works were finished in 2012. The section 'Bologna' – 'Conca D'Oro' was inaugurated in June 2012.

The geology along the Metro B1 stretch is depicted in Figs. 1 and 2, respectively. In the area of 'Bologna Station' the soils interested by grouting and tunnelling are pyroclastic formations and recent alluvial deposits.

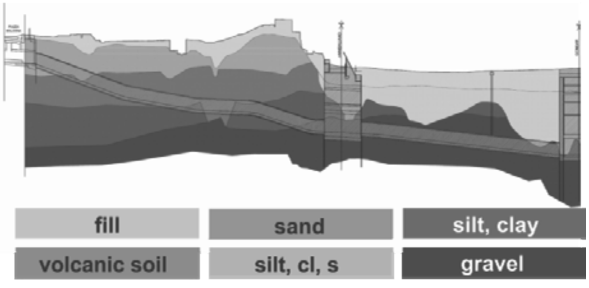

Figure 1. Geological cross section between 'Bologna Station' (left hand side) and 'Gondar Station'.

Grouting and tunnelling works for the 'Ionio Station' were mainly made in Paleotevere gravels or silts and sands, respectively.

The groundwater table for the entire Metro B1 is located at few meters below ground surface. Table 1 provides an overview of the main soil layers and their geotechnical parameters.

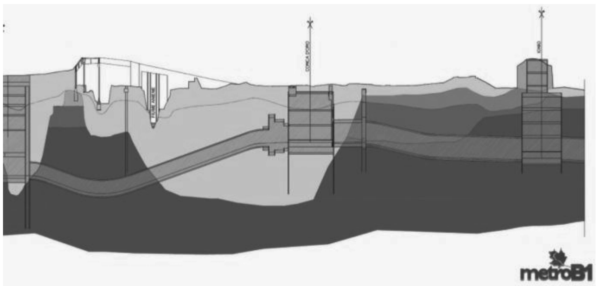

Figure 2. Geological cross section between 'Gondar Station' and 'Ionio Station' (right hand side); for legend see Fig. 1.

Table 1. Geotechnical parameters for main soil layers.

unit	*c[kPa]*	*phi[°]*	*E[MPa]*
Man-made ground	0	30	20-70
Pyroclastic	0-20	28-38	90-400
Recent alluvial OC	15-45	19-27	60-160
Recent alluvial NC	0-5	28-30	60-160
Paleotevere-sand	0-30	26-37	80-200
Paleotevere-silt/clay	5-30	20-34	80-200
Paleotevere-gravel	0-10	32-41	100-300

2 COMPENSATION GROUTING FOR SHALLOW FOUNDATIONS

Compensation grouting is frequently applied in urban tunnelling projects to reduce the impact of tunnelling to adjacent buildings providing the advantages of an active protection measure according to the observational method. For a detailed description of the compensation grouting method see Falk and Kummerer (2012). In the particular case of Metro B1, compensation grouting substituted the original design with full face (jet) grouting of the cross section for the following reasons:

- reduction of space requirements as all activities were located within small shafts and one site installation area
- no additional area needed to provide the space for drilling rigs (e.g. on roads closed for traffic)
- simple drilling geometry with two parallel grouting pipe (TAM) arrays avoiding complex 3D drilling set-ups
- reduction of spoil resulting from jet grouting
- real-time monitoring of critical buildings with the possibility of actively correct undue deformations.

Before implementing compensation grouting for 8 critical buildings close to 'Bologna station', the actual state and tolerable deformations of these structures were assessed in comprehensive studies. The allowable maximum absolute and differential settlement was defined with 15 mm and 1/500, respectively. Deformation analyses based on the well-known soil behaviour showed that for the assumed volume loss of 0.6 to 2.0% (with a tunnel diameter of 6.8 m) settlements would exceed the allowable value. To prove the efficiency of compensation grouting, a full-scale field trial under similar conditions was performed demonstrating that a controlled heave of an isolated footing of 4 cm was achieved after a cycle of repeated controlled grouting steps with special cement based grout mixes. For a detailed description of the design and the field trail see Sciotti et al. (2011).

The grouting strategy identified by means of the field trial was applied to these building protected by 197 TAM pipes installed on a ground surface of approx. 3,000 m². All buildings were pre-heaved by max. 5 mm to prove the immediate reaction for concurrent grouting. To guarantee high accuracy drillings, all TAMs were installed with the Horizontal Directional Drilling-Technology. For 'Building 1' the grouting pipes had a radius of 120 to 140 m (see Fig. 3). Although the minimum distance of the TAMs was less than 1 m from the foundation, no significant settlement was measured during drilling.

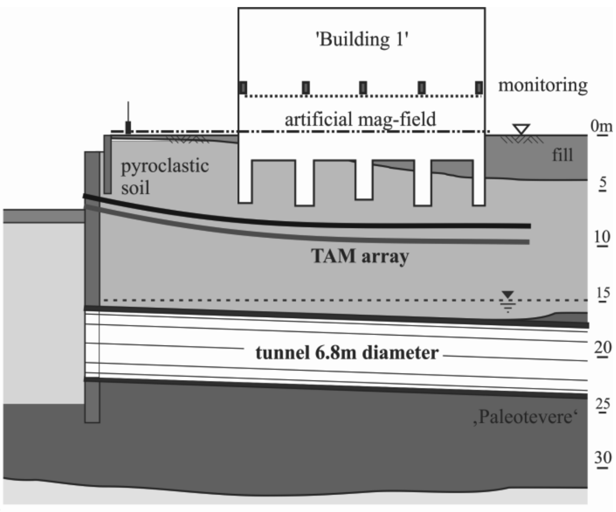

Figure 3. Cross section of compensation grouting for 'Building 1'.

In total, more than 100 monitoring points were installed for controlling the compensation grouting operation with a zero reading before any activity on site.

As all grouting parameters (e.g. TAM spacing, grout mixes, injected volumes) were tested during the field trial, the grouting operation was very efficient during the excavation of both tunnels. The settlements were below the tolerable values. Fig. 4 shows both tunnels from the final station shaft.

Figure 4. Picture of finished upper tunnel and TBM in end position for lower tunnel.

3 COMPENSATION GROUTING FOR PILED FOUNDATIONS

Compared to the conditions of the above mentioned works with relatively shallow foundations, circumstances were different at 'Ionio Station' (Kummerer et al. 2012). The tunnel diameter was 9.8 m (double track tunnel). The grouted and excavated soils were gravels with a low content of fines. And more important, all buildings are founded on piles with a typical diameter of 600 mm and a pile length of max. 19 m. Therefore additional studies were necessary to address the very complex situation of compensation grouting for piled foundations.

As a consequence and due to the fact that worldwide only limited experience was available for grouting underneath piled foundations, an additional real-scale field trial was performed. For the trial an already excavated station was chosen representing conditions similar to the actual compensation grouting works. A dead load of approx. 50 kPa above 9 piles with a length of 15 m and 20 m respectively represented the in-situ conditions (see Fig. 5).

Figure 5. Photo of 'Ionio Station' full-scale field trial.

Fig. 6 shows the schematic cross section of the field trial with ballast, piles and monitoring (liquid levels, pressure cells, precise levelling and incremental extensometers).

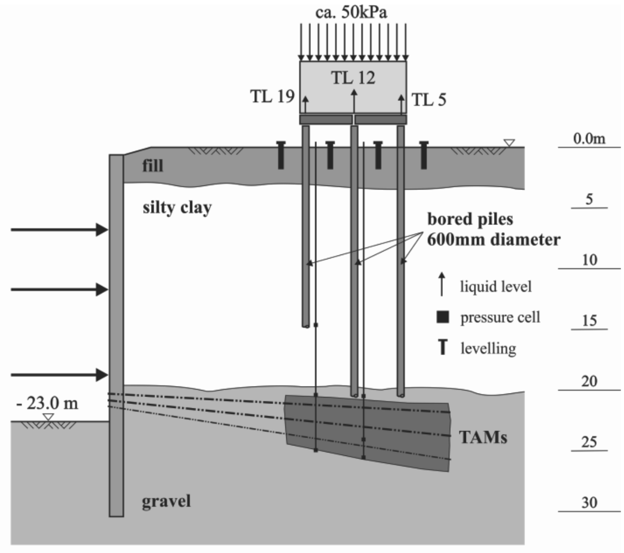

Figure 6. Field trial for real-scale testing of the response of grouting underneath piled foundations.

Due to the high void content of the soil a considerable grout take was observed during the pre-treatment phase. The targeted heave of 20 mm was achieved with grout efficiencies comparable to those with shallow foundations. The results can be seen in Fig. 7 for selected water levels.

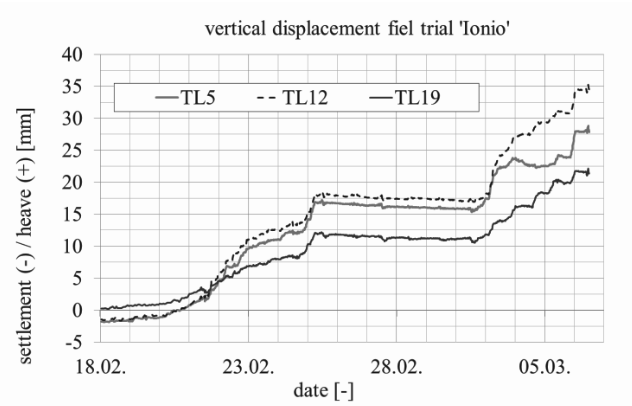

Figure 7. Vertical heave of selected pile heads monitored during the heaving phase.

With the results obtained from the field trial the protection of 4 buildings was designed. For the TAM arrays two deep shafts were realized in closest vicinity to service lines such as a high voltage power line and adjacent apartment buildings (see Figs. 8 and 9). For the shaft construction Soilcrete-jet grouting was utilized for the lateral walls (two rows of columns) and the sealing slab as it proved to be a flexible and reliable solution. Buildings were monitored with real-time monitoring during jet grouting. The control of the jet grouting elements and the water tightness of the shaft was performed by means of pumping tests and thermal leakage and diameter controls.

From the shafts (max. 24 m deep, inner diameter 5.0 m and 6.0 m, respectively) two layers of TAMs at a maximum depth of approx. 20 m were installed without disturbance of the adjacent structures. Due to the variable pile length, TAMs were implemented at different depths in order to keep the distance between TAMs and piles constantly at 1.0 to 1.5 m.

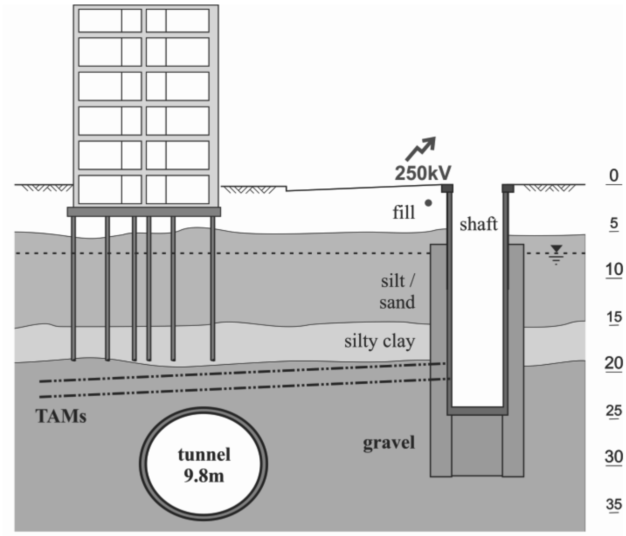

Figure 8. Schematic cross section of piled foundation at 'Ionio Station'.

Figure 9. Arial view of finished shaft with 6 m inner diameter and 24 m depth.

The deformation of 'Building 146' is represented in Fig. 10. Generally the passive effect of the pre-treatment phase reduced the deformation, with active grouting an additional reduction of absolute and differential settlement was obtained.

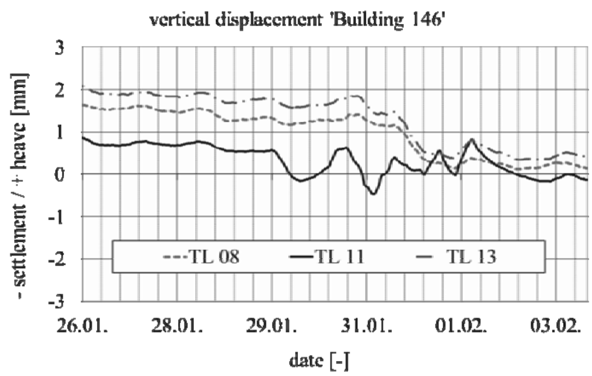

Figure 10. Vertical response of buildings during TBM excavation.

4 COMPARISON OF DEFORMATION BEHAVIOUR BETWEEN GROUTED AND NON TREATED AREAS

The efficiency of compensation grouting was proven during the TBM excavation underneath 'Building 164' (see Fig. 11). This 5 storey building with shallow foundations is located next to the exit shaft which is filled with water sealing material to allow for the entrance of the TBM. The soil profile is determined by fill and sandy soil, underlain by gravel in the tunnelling section. The groundwater table is 4 m below ground surface. The cover between the footings and the 9.8 m diameter tunnel is ca. 13 m. The TAM array with two layers of grouting pipes was designed in function of the risk assessment.

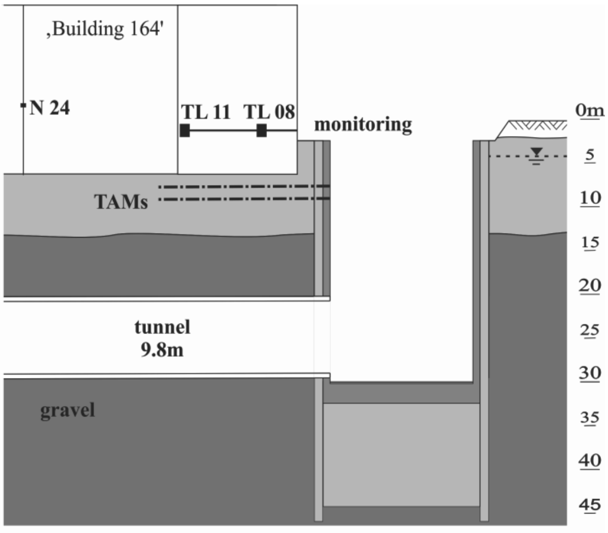

Figure 11. Cross section of 'Building 164'.

The plan view of 'Building 164' with respect to the tunnel excavation and the exit shaft is depicted in Fig. 12. The TAM array covers the building only in the part of the building where a major risk of settlement was assumed when entering in the final shaft (while cutting the diaphragm wall). A large number of water gauges and precise levelling points were installed on the structure to assess the deformation.

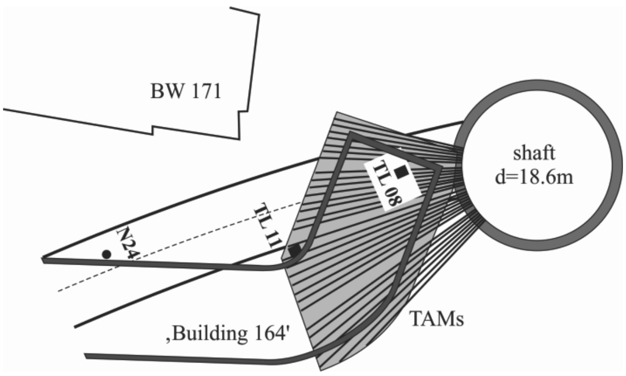

Figure 12. Plan view of the 'Building 164' next to the exit shaft.

The implementation of the grouting pipes took place after settlements were observed during the approach of the TBM. Fig. 13 shows the vertical displacement of 2 monitoring points of 'Building 164' during the excavation of the TBM. These instruments are the liquid levels TL 08 and TL 11 installed in the compensated area. To compare with the settlement in the untreated zone, precise levelling point N 24 is also indicated in Fig. 12. In monitoring point N 24 the maximum final settlement for this building was measured with 20 mm after the TBM has passed. Both liquid levelling points clearly show the effect of grouting with a maximum settlement of 10 mm (TL 11). The settlement during the tunnel excavation was significantly lower (approx. 3 mm for TL 11). It has to be mentioned that settlement compensation in the transition zone between the untreated and the grouted area had to be limited in order to avoid undue differential settlements.

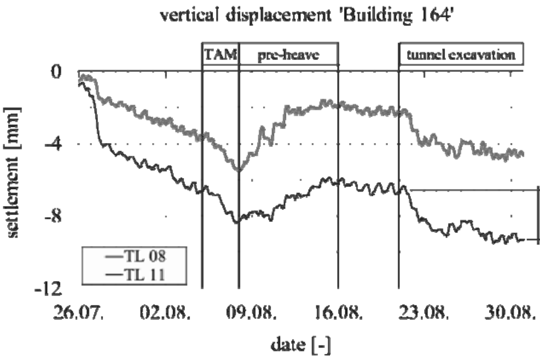

Figure 13.Vertical displacements due to tunnelling and grouting activity in distinct monitoring points.

5 CONCLUSIONS

Compensation grouting was used for the construction of Metro B1 in Rome to limit absolute and differential settlements in critical areas, where the risk of damaging the buildings has high. The buildings were founded on shallow foundations and piles.

Due to compensation grouting operations, settlements were significantly below the tolerable values and confirm the efficiency of the building protection measure technically and economically both for shallow and deep foundations.

For the design of these compensation grouting projects it was fundamentally to establish the grouting strategy by means of full-scale field trials.

6 REFERENCES

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