Mitigation of the effects induced by shallow tunneling in urban environment: The use of ‘compensation grouting’ in the underground Line B1 works in Rome

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ABSTRACT: The new Underground Line B1 works in Rome involve the construction of three new stations and of about 7 km of single-track tunnels (i.d. 5.80 m) by means of two TBMs. The tunnels must be realized in heavily built-up areas, often with multi-storey buildings, both in masonry and in concrete. In the stretch near Bologna Station of the already operating Line B, the tunnels run at only few meters from building foundations. The settlements analyses carried-out in the design stage indicated the necessity of mitigation measures. Environmental constraints, building characteristics, geometric and geotechnical situations directed the choice towards the ‘Compensation grouting’ method as the best mitigation measure. Numerical analyses and one trial-field were used for exhaustive design definition. At the end of September 2010 the first tunnel under compensation grouting area was completed and the in situ monitoring data confirm the effectiveness of the chosen mitigation.

1 THE NEW METRO LINE B1 IN ROME

1.1 General information

Line B1 is a branch line of the existing “Line B” and extends for about 7.5 km, from Piazza Bologna to the Rome orbital motorway. Its catchment area is the northeast quadrant of Rome—in Municipal District II, III and IV—where more than half a million people live.

The section currently under construction starts from Bologna Station of the already operating Line B; it stretches entirely underground over a distance of about 4 km; it involves 3 new planned stations and about 7 km twin single-track tunnels. The Client is Roma Metropolitane, an independent subdivision of the Municipality of Rome. The main contractor is Salini Costruttori Spa while the main designer is Tecnimont Spa (Rome, Italy). For the Compensation Grouting the sub-contractor is Keller Fondazioni Srl and the specialist designer is Stone Srl.

The construction works started in November 2005 and the planned schedule foresees the completion in October 2011. The tunnel excavation just started at the end of 2008 and it takes place from the Conca d’Oro station towards the Bologna station, which is the connection to the existing line.

1.2 Geological features

On the whole Line B1, the typical excavated soils consist of fluvial-lacustrine recent sedimentary formations. The geological sequence comprises a base deposit of fluvo-palustrine gravel of Pleistocene age, overlain by a layer of clayey silts and sandy silts, both of Pleistocene age. Frequent and relatively deep ancient ditches filled by alluvial silty-clayey and sandy deposits cut into the Pleistocene deposits. A layer of made ground of varying thickness including relics of ancient structures covers everywhere the natural soil profile. The piezometric level is few meters below ground level.

Several geotechnical site investigations have been performed during the designing phases. The main geotechnical parameters of soils to excavate are reported in Table 1.
relationships based on the Gaussian settlement profiles (e.g. Peck 1969; Attewell & Farmer, 1974; Attewell, 1977; O’Really & New 1982; Shirlaw & Doran, 1988). Some specific cases, characterized by shallow cover or large predicted settlements, required a more detailed study, carried out by means of numerical analyses, which also allowed to evaluate the effectiveness of remedial measures.

The empirical predictions were performed considering the following input parameters range: a volume loss from 0.6% to 2%. The smaller values are the design values and the most likely considering the excavation techniques and the mechanical characteristics of the soil, the larger values was adopted as a worst scenario values.

The assessment of risk of damage to buildings due to tunneling has been developed according the Mair, Taylor & Burland approach (1996), which is based on the relationship between category of damage and limiting tensile strain. The acceptable damage categories have been considered from degree 0 to 2, when structural integrity is not at risk and damage can be repaired readily and economically. For degrees of damage higher than 3, protective measures have been planned.

### 1.3 Tunnel design

The Line B1 projects involve tunneling and deep excavations in densely developed areas of Rome. As a consequence, the main issue of the B1 line design has been to minimize the impact on the urban environment. An impact of tunnelling is subsidence and its effects on structures and services. Thus, in the planning process it was decided to set the tunnels relatively deep (30–35 m below ground level) in order to mitigate interactions with pre-existing structures (building foundations, gas and water pipelines, etc.).

Tunnels are excavated through recent alluvial soils, characterized by poor geotechnical properties, below groundwater table (up to 25–30 m).

Due to complex geotechnical conditions and potential risks for buildings and services, tunnel excavation by closed-face shield machines, in which a pressure is applied to the tunnel face, has been considered the most reliable method to control surface displacements. Taking into account the variability of geotechnical conditions along the route, an Earth Pressure Balance Shield has been chosen.

The evaluation of face stability pressure was performed considering different conditions (“earth pressure at rest”, “active earth pressure”) by means of analytical analyses (characteristic line method, Anagnostou and Kovari (1996) equations, finite difference numerical analyses on cross and longitudinal sections). In this way the upper and lower limits for the face pressure were defined as well as possible in design phase.

The study of the tunnelling-induced settlements has been performed following different approaches, depending on the complexity and peculiar conditions along the route. In most cases the displacements fields induced by tunnel construction activities in greenfield conditions have been computed using well established empirical relationships based on the Gaussian settlement profiles.

### 2 Mitigation Measures: Compensation Grouting Application

Generally the excavation by TBM must be considered as the first mitigation measure with regard to settlements. A correct approach and an effective management of TBM boring are essential and indispensable for a safety tunneling in an urban environment.

As mentioned above, when the design analysis (carried out on the basis of predictable TBM performance) pointed out situations in which the risks exceed the acceptable values, other protective measures were planned since the design stage.

Where the tunnels run to the side of buildings, the mitigation measures consist of jet grouting treatments to protect the foundations, bounding subsidence effects outside from the ‘effective foundation volume’. The execution of vertical jet-grouting columns row from the ground level (just between the building and the tunnel), of a sufficient length to cover the whole subsidence curve induced by tunneling, is able to minimize foundation settlements.

In the last stretch towards the existing Bologna Station of the already operating Line B the tunnels have instead to run under existing buildings, at only few meters from their foundations.

Most of the buildings under-passed in the above identified stretch of Line B1 were built among
1930 and 1940; only two more recent buildings were built in 1954 and in 1960. Eleven buildings are made in masonry, and only three in reinforced concrete. The buildings have several main storeys—up to ten—with one basement under road level. Some of the buildings have direct (shallow) foundations, at about 3–5 m below ground level. The others have indirect (deep) foundations—as ‘pozzi e barulle’—up to 12–15 m below ground level.

In this stretch the geological sequence is mainly characterized by volcanic deposits. The Pleistocene deposits (fluvio-palustrine gravel, clayey silts and sandy silts) are covered by pyroclastic soils, pozzolanic ash and not-well-cemented tuffs, with granular and/or cohesive behavior—both of Pleistocene age. A layer of made ground of varying thickness covers everywhere the volcanic deposits.

In this situation it was necessary to identify a different protective measure. Environmental constraints, building characteristics, geometric and geotechnical situations directed the choice toward the ‘Compensation grouting’ method. By means of empirical methods and numerical analysis, the study of the tunneling-induced settlements performed the effectiveness of ‘compensation grouting’ as remedial measure theoretically considered to be the most valid.

3 COMPENSATION GROUTING METHOD

Grouting as a measure for the settlement correction dates back in the 1930s where it was applied for the re-levelling of pavement slabs. From then, displacement grouting was frequently used to deal with settlement problems where active control of the deformation according to the observational methods was needed. Various grouting technologies such as compaction grouting or fracture grouting were developed for different soil conditions (Harris 2001). Recently compensation grouting was employed in infrastructure projects with challenging geotechnical conditions.

Compensation grouting is performed by introducing a grouting array between the structure and the source of the settlement, i.e. the tunnel excavation (see Fig. 1). The reduction of the settlements has to be established during the design process and is triggered by the allowable settlements of the structure.

In the majority of settlement compensation projects the fracture grouting technology is adopted. Soil fracturing means to fracture the ground in a controlled manner in order to create a skeleton of cement fractures (see Fig. 2). By repeating the process of fracturing several times, it is possible to obtain the designed settlement reduction along with an improvement of the mechanical properties of the soil.

4 DESIGN OF THE COMPENSATION GROUTING APPLICATION

For the design of the project detailed analyses were carried out. The considerations included the settlement prediction with numerical and analytical methods as well as the structural analyses of the buildings potentially affected by the tunnels excavation.

In the first step of the design the expected deformation was calculated using the empirical Gauss method. With this method reliable settlement patterns were obtained for each building assuming a “design” volume loss of 0.6%.

These settlement troughs were used as the deformation load case for the structural analyses. In Figure 3 an example of the structural deformation is given.

By comparing the excavation induced stresses and the structural resistances the allowable absolute and differential settlement/rotation of the treated buildings was determined, considering two different building types (see Table 2). Building type 1 is the standard type with larger allowable settlements, whereas type 2 is more sensitive to settlements.
Figure 3. Imposed settlements as load case for the structural analyses.

Table 2. Allowable deformation in function of building type.

<table>
<thead>
<tr>
<th>Type</th>
<th>Attention</th>
<th>Alert</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Absolute settlement</td>
<td>-5 mm</td>
<td>-10 mm</td>
</tr>
<tr>
<td></td>
<td>Rotation</td>
<td>1/1000</td>
<td>1/500</td>
</tr>
<tr>
<td>Type 2</td>
<td>Absolute settlement</td>
<td>0 mm</td>
<td>-5 mm</td>
</tr>
<tr>
<td></td>
<td>Rotation</td>
<td>1/1000</td>
<td></td>
</tr>
</tbody>
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All above mentioned values refer to the absolute zero-measurement (before any activity).

The allowable deformation was divided in three different intermediate levels. The aim of the compensation grouting activity was to maintain recorded settlement within the “alert level”. To this scope specific procedures were established on the basis of monitoring data. Below the “attention-level”, the equipment is kept ready for grouting, but grouting activity is generally not performed. Between the “attention-level” and the “alert-level” compensation grouting has to be performed in order to keep the deformation below the “limit-level”. Moreover, a reduction of the TBM-speed was considered as additional measure. Beyond the “limit-level, the tunnel excavation would have been stopped and additional measures implemented.

5 FIELD TRIAL TESTS AND OPERATIVE CHOICES

A comprehensive field trial (Fig. 4) was performed prior to the compensation grouting job in order to verify the applicability of the proposed technology to the geotechnical and structural situation of Piazza Bologna and to establish the operative details and choices. The location of the field trial was chosen close to Piazza Bologna where very similar soil conditions were given. The aims of the field trial where:

- to identify a suitable drilling method from shafts;
- to verify that a controlled lift of the foundation element was achievable;
- to establish the grouting parameters in terms of grout mix, volumes pumping rates as well as grouting efficiency;
- to test the appropriate monitoring systems for real-time measurement.

The field trial was started in December 2008 with the construction of a footing consisting of 9 bored piles with 600 mm diameter and a length of 7.5 m. This foundation was chosen in order to simulate the special “shaft”-type foundation which is typical for this zone of Rome. The head of the piles were connected with a concrete block of dimensions of 2.2 × 2.2 m and 0.5 m thickness. Moreover a shaft was realized by means of 21 bored piles, 600 mm in diameter and ca. 12 m long. This circular shaft had an inner diameter of 3.6 m and ca. 10.6 m depth.

Thereafter a monitoring system was installed, integrated 13 liquid leveling points including the reference point, 38 precise leveling points and 3 inclinometers. The plan view of the field trial with the shaft, the theoretical position of the grouting pipes and the monitoring system is depicted in Figure 5. The field trial area was divided in two distinct zones—one with the “footing-zone”, the other as “green field”-area. This choice was made to investigate to which extent the grouting would influence the adjacent area. For the installation of the grouting pipes (Tube a Manchettes) nine drillings were made, five drillings reaching the zone of the more distant footing zone and four additional for the green field area. The maximum drilling length was 28 m (see cross section in Fig. 5).

For the drilling a casing of 114 mm with controlled back-flush was utilized. After the completion of each drilling, the deviation was monitored with the Maxibor II equipment. A maximum horizontal deviation of 1.3% and vertical deviation of 0.9% was measured.

After these measurements the casing was withdrawn while filling the annular ring with appropriate sleeve grout. The settlement of the footing during the drilling phase was 1 mm.

At the beginning of the grouting works it was verified that all sleeves were groutable. Thereafter the heaving of the footing was commenced. The goal of the trial was to heave the footing up to 40 mm in various steps. This is the maximum
expected value for settlement in greenfield conditions in the area of compensation grouting application.

For the evaluation of the grouting process the specialist software GroutControl was applied. This software allows for the combined visualization of grouting and monitoring data.

The grouting phase was divided in the following steps:
- Pre-treatment grouting
- Conditioning grouting
- Compensation grouting

5.1 Pre-treatment grouting phase
The aim of this phase was to generate an initial heave of the footing by 1–2 mm in order to establish the appropriate grouting parameters for controlled heave. The uniform heave was obtained after up to 5 grouting steps per sleeve with volumes of 50–100 l/sleeve. The total volume grouted in this phase was 5.1% of the volume of grout treated underneath the footing.

5.2 Conditioning grouting phase
A uniform uplift of 5 mm had to be obtained in this phase. In a maximum number of 4 grout steps/sleeve this phase was completed. It was shown that no influence of the grouting underneath the footing was measured in the green field area.

5.3 Compensation grouting phase
In this phase an absolute heaving to 40 mm had to be achieved, corresponding to a tunnel induced volume loss of more than 1%. Figure 6 shows the vertical displacement of selected points in course of the field trial. A heave of 40 mm was measured on the footing (TL 5) and the adjacent water levels (e.g. TL 7). The final uplift of the distant water level TL 2 was only 6 mm. The Field trial finished in March 2009.

After the field trial an inspection of the grouted area was made. Therefore a borehole was drilled and disturbed soil samples were taken.

Figure 7 shows the result of one soil sample with the cement fractures (red color due to colored grout).

The grout take during the whole field trial was evaluated with GroutControl utilizing a 3 × 3 m grid showing the mean pressure and the volume grouted in the unit area (Fig. 8). Moreover the theoretical and real position of the grouting pipe with the sleeves is depicted.

The maximum grout take was 350 l/m² with the mean injection pressure ranging from 16.5 to 25 bar.

Based on the above mentioned grid the grout efficiency was determined. The grout efficiency is defined as ratio of “heave volume” and “grout volume” where the heave volume is the uplift measured by means of monitoring points. For the...
Works were started in October 2009 with the installation monitoring system and the construction of the shafts.

Building No. 1 was constructed in 1935 and has a masonry structure with six floors. During the construction of the Metro B line this building experienced significant deformation, so the soil conditions can be considered to be disturbed (Fig. 9).

The Grouting pipes were installed from the exit shaft of the TBM, but due to geometrical circumstances straight drillings were not feasible. Therefore curved directional drillings from the first excavation level had to be made. The curvature of the drillings is about 120 m, the minimum distance to the foundation ca. 1 m.

A Paratrack probe was utilized for the directional drilling. The three-dimensional reference for the steering process was generated by means of an artificial magnetic field. After completing the pilot hole a casing was washed over the drilling rods in order to have defined conditions for the installation of the 2” grouting pipes with a valve distance of 50 cm. In total 25 drilling were made for the protection of this building (see plan view in Fig. 10).

area of the footing with 16 m² of influence, the mean grout efficiency during the heaving phase was about 7%.

6 SITE PERFORMANCES

The compensation job had the aim to cover eight buildings where the design showed that high damage risk was likely without protective measures. Especially two buildings were particularly critical, namely Building No. 1 and 16.
The concrete structure Building 16 was constructed in 1963 with 8 floors. Due to the large basement floor, the cover between the foundation and the tunnel crown is only 2.8 m (Fig. 11). The TAM array with four layers was drilled from a shaft with elliptical shape of about $6.5 \times 4.2$ m. Two layers with 2″ steel pipes were used for compensation grouting purposes. Due to the very limited cover additional soil treatment was made with two layers of fiberglass-tubes in the crown of the tunnel section.

In the course of the projects, a total of 197 drillings were made with a length of ca. 6,700 m from 4 shafts. With the concept of two layers a better pre-treatment of the soil was achieved as well as more operational reliability. The maximum distance between the TAMs was ca. 3 m. The drilling deviation measured with the Paratrack probe and checked with the Maxibor system for 50% of the drillings turned out to be about 1%. Drilling induced settlements were 1–2 mm.

The mixing and grouting plant was selected according to the experiences made with the field trial. The main components are a Keller colloid mixer, 12 pumps for a maximum pressure of 80–100 bar and 2 silos. With this plant various grout mixes based on water, cement and filler were mixed in place. From the central mixing plant the grout was pumped to the two grouting containers which distributed the suspension to the four shafts. The mixing/grouting capacity was estimated for an average TBM advance up to 20 m per day, considering a grout efficiency of about 7%. In spring 2010 grouting was started with the pre-treatment. Figure 12 shows the grouting process form the exit shaft close to Building 1.

In the site office located next to the plant all data from the project are collected and in progress analyzed: data from the real-time monitoring system, from the TBM excavation control system and from the grouting work012

According to the preliminary settlement analyses the designer decided to introduce a pre-heave to all the buildings after the pre-treatment of the soil was finished. With the pre-heave more operational range was gained as it increases the allowable deformation range. The value of 5 mm was considered to be a reasonable value as it represents 30 to 50% of the expected settlement for a standard volume loss.

![Figure 11. Schematic section of Building 16.](image1)

![Figure 12. Grouting activity from the exit shaft.](image2)

![Figure 13. Settlement-time diagram for building 16.](image3)

![Figure 14. Contour plot of total grout take.](image4)
This phase was terminated in July 2010. Compensation grouting was performed in September 2010 for the first tunnel (shallow tunnel) buildings under-passing. The duration of the compensation period was 16 days. Due to correct design and adequate operative in progress management of compensation grouting activity, the recorded settlements were generally rather limited and always lower than alert-level values. Particularly the vertical displacements of monitoring points of Building 16 during the tunnel excavations (referred to the absolute zero) are shown in Figure 13, with displacements of less than 5 mm.

The total injected volume is shown in Figure 14. On the whole intervention area for the first tunnel, the total grout volume for the pre-treatment, pre-heaving and compensation was 515 m³. No interference with the tunnel operation due to grouting was observed.

7 CONCLUSIONS

On the new Line B1 works a correct design and operational approach have allowed to face—with excellent results—a situation particularly complex, by means of ‘compensation grouting’ method. The recorded site performances show an efficacious control of building settlements induced by mechanized excavation of the tunnel. The calibration of compensation grouting application by a field trial test has been a key to success (Fig. 15).

REFERENCES