Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art – Peila, Viggiani & Celestino (Eds)

Warsaw line II metro extension: TBM excavation under historical buildings in urban environment

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ABSTRACT: The TBM excavation for the Eastern extension of the Warsaw line II metro has been completed in January 2018 by Astaldi/Gulermak joint venture. Excavation involved mainly fine and medium sands below water table which created a challenging environment for Earth Pressure Balance (EPB) TBM works. In order to reduce settlements at ground level for selected historical buildings, ground improvement was carried out through permeation grouting with the aim at reducing volume loss during excavation and inducing an initial heave of the buildings. Also, high-standard TBM performance was achieved with the use of bentonite and polymers, specific grout mix and controlled face and grout pressures. Extensive monitoring was carried out through manual and automatic measurements and results showed small movements of the buildings and very small damage. This paper is aimed at describing the challenges faced for the TBM excavation, the adopted solutions and the most relevant results.

1 INTRODUCTION

On March 2016, the Municipality of Warsaw, by the Investor Metro Warszawskie appointed Contractor Astaldi S.p.A for the North-East extension of the Metro line II, including the

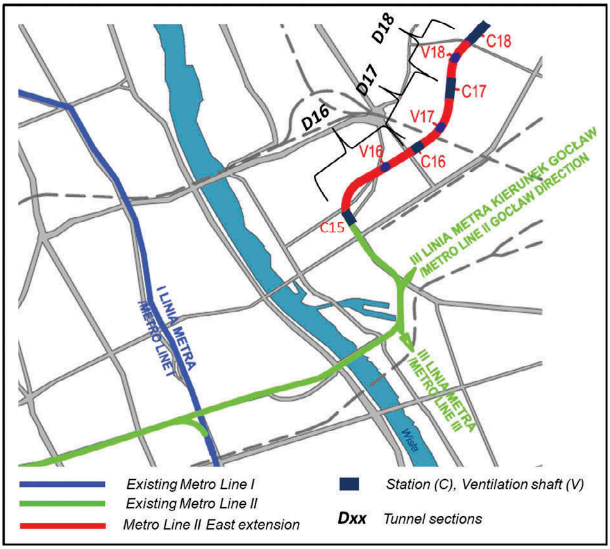

Figure 1. Tunnel works plan.

construction of 3 underground stations, an holding track and double twin tunnels on the area of Targowek-Praga districts. The section is the extension of the central part of the Metro line II, built by Astaldi and Gulermak joint venture and active since March 2015. The 6,3 km construction of the metro section was subdivided into 2x2,22 km long shield tunnel, and the rest on cut&cover technology for the station and ventilation shaft executions. Figure 1 shows a layout sketch of the whole project. The focus of this paper is the tunnel section D16 which is the most densely inhabitated. The 2 single-track tunnels have an inner diameter of 5,4m and the lining is made up of 5+1 precast segments with a thickness of 30cm. Classic steel reinforcement cage has been used and polypropylene fibers have been added to the concrete mix mostly for fire protection.

2 GROUND CONDITIONS

The tunnel route of interest is located within the area of regional geomorphological unit called Wisła River drainage basin. The morphology results from the glacial retreat occurred during the Central-Poland Glaciation and the subsequent fluvial processes which were continuously affecting the area during the Eemian Interglacial period, the Wisła River Glaciation, and the Holocene. The tunnel route encountered two geological formations (Pliocene and Quaternary deposits) other than anthropogenic fills. On a geotechnical point of view, the following units have been selected (from top to bottom):

- Fill (Holocene). It consists of uncontrolled and non-uniform anthropogenic fills of diversified origin (filled up old clay pits, cellars, old pavements and road sub-grades, mainly created in the course of war damages and post-war reconstructions) with a maximum thickness of 3 meters;
- Unit 4 (Quaternary). It consists of granular non-cohesive alluvial soils originating as fluvioglacial deposits, including mainly medium grain sands and coarse sands. Maximum thickness along the route is about 13 meters. N_{SPT} varying between 9 and 20 and a CPT cone penetration q_c of approx. 4MPa to 10MPa (with local peaks up to 15MPa);
- Unit 3 (Quaternary). It consists of granular non-cohesive alluvial soils originating as fluvioglacial deposits (Eemian interglaciation). These include mainly medium grain sands and coarse and dense sands. Maximum (verified) thickness along the route is about 15m. N_{SPT} varying between 16 and 40 and a q_c of approx. 15MPa to 45MPa;
- Unit 2 (Quaternary) – locally present. It consists of cohesive soils originating as marginal deposits of Odra glaciation. These include mainly clays and silty clays found in hard-plastic state. Maximum (verified) thickness along the whole tunnel route is about 13 meters. N_{SPT} varying between 14 and 17 and a q_c of approx. 2MPa;

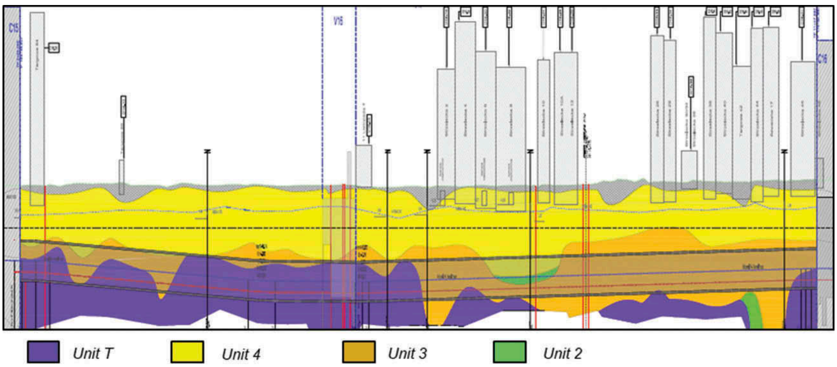

Figure 2. Extract from the geotechnical profile along the D16 Right tunnel excavation (different scale in x and z).

– Unit T (Pliocene). It consists of cohesive soils originating from lacustrine deposits of Odra glaciation. These include mainly tills and silty tills. Maximum (verified) thickness along the route is about 10m. N_{SPT} varying between 9 and 15 and a q_c of approx 1–2MPa increasing with depth at about 1MPa/m.

In the area of interest, a single aquifer exists and it is related with the alluvial sand and gravel deposits. The water table level is found at approx. 2–3m below ground level and the aquifer is easily rechargeable due to the high permeability of the non-cohesive water-bearing strata.

The area along the tunnel route of interest is generally flat with the only exception of a railway embankment to be underpassed.

3 SITE CONDITIONS

While for the first 2 tunnel sections (D17 and D18) mostly green areas can be found at ground level, the area above the last tunnel section (D16) is densely built. Moreover, most of the buildings were built before the second World War and it is a almost a unique scenario in Warsaw since the city was highly destroyed and damaged during the war. These are generally 4–5 storeys masonry buildings with 1-level basement and founded on strip brick foundations; timber elements may also be present at the building roof or floor slabs. Many of them are in poor conditions and some of them show an extensive presence of cracks and spalling. Minor refurbishment and structural works were carried out in selected buildings during the years; just few of them have been completely re-built.

The 2 tunnels run along Strzelecka street directly below many of such buildings or in the close vicinity. In particular, the left tunnel is below one side of the buildings with the risk of inducing detrimental differential settlements. The soil overburden generally varied between approx. 7,7m and 12,1m.

4 TBM EXCAVATION

As in the Central part of the Line II metro, a mechanized excavation technology has been adopted for the tunnel excavation in order to minimize the impact on the city (reducing construction site areas, disturbance to public and traffic, damages to existing buildings and utilities, vibrations, etc.), improve safety of the workers and, at the same time, guarantee a high performance in terms of production and cost.

Two of the Earth Pressure Balance (EPB) TBMs successfully used in the heterogenous geological conditions of the Central part of the Line II were therefore renewed and adopted for the new excavation. At design stage it appeared already clear that excavation conditions

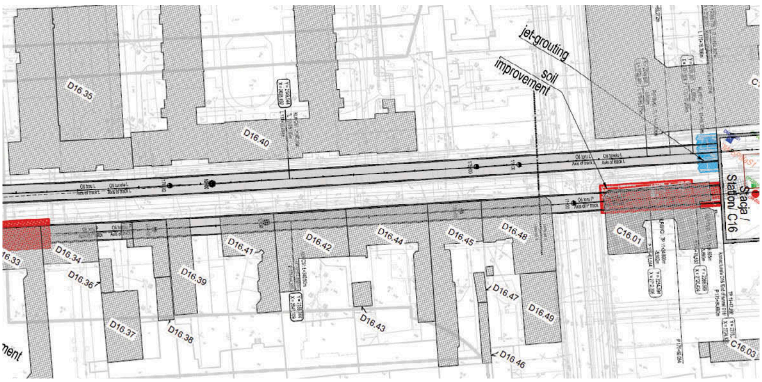

Figure 3. Plan view of the building and tunnel location in the first part of D16 tunnel section.

Figure 4. One of the buildings that were underpassed by the TBM (existing conditions prior to excavation).

along this metro extension were challenging for several reasons: in some areas the ground conditions - clean sands and gravel below groundwater table often without any fine soils - were at the edge of the use of a EPB machine; excavation was generally shallow with several buildings and utilities above; buildings were often old, masonry-built and in poor conditions. Therefore, both prior to TBM launching and during the initial part of the excavation (on green areas), a series of improvements have been applied to minimize the volume loss, and therefore the subsidence at the ground level, and optimise the excavation process:

- Design pressure at the TBM front was increased by approx. 0.3bar comparing to values initially derived by standard calculations for face stability (Jancsecz & Steiner, 1994; Anagnostou & Kovári, 1996). Therefore face pressure was usually between 1.5bar and 1.7bar. Nevertheless, TBM was still able to excavate at good pace and without significant high thrust or torque;
- Although conditioning was used, due to the lack of fine fraction, the excavated soil was very liquid creating problem from a logistic point of view on handling the muck removal and affecting the control of the earth pressure at the excavation front. To face this problem, Contractor, Designer and Supplier decided to use, with very low dosage, a lubricating polymer able to decrease the water content of the muck so to better create a plug in the excavation chamber. This allowed the TBM operators to better manage the screw conveyor and hence the earth pressure at the TBM face;
- In selected sections bentonite was injected around the shield of the TBM during each advancement in order to have more plastic material around and at the tail of the shield;
- The bi-component grout quantity injected to the anular gap at the tail of the TBM has been generally higher than design value. Main parameters have been also improved; in particular, the gel time was decreased from 9 seconds to 7 seconds in order to have a more viscous grout. This allowed to achieve the design back pressures and, hence, to keep the cavity more stable. Design values of back-pressures were generally 0.3bar higher than face pressure.
- An appropriate specific configuration of cutting wheel dressing, with 14 disc cutters and additional rippers has been adopted; this was aimed at better protecting the excavation profile of the buckets from the gravels and pebbles encountered along the excavation and

Figure 5. Break-through of the Left TBM at C15 station.

allowed considerable savings in economic terms and time schedule avoiding any additional maintenance stop. This was decided following the arrival of the TBMs into the first station where a high wear of the cutter head tools was noted.

The TBM excavation works were successfully completed in January 2018. In the D16 tunnel, where high attention was paid due to the presence of historical buildings and utilities, measured Volume Loss was generally smaller than 0.3% with settlements of the buildings lower than 1.0cm and very minor damages recorded.

5 IMPROVEMENT WORKS

5.1 *Ground movement and damage assessment*

Ground movement assessment was carried out according to Burland methodology (Burland, 1997) with appropariate safety factors adopted to take into account the conditions of the buildings and their susceptibility to damage (vulnerability). A Volume Loss of 0.4% has been initially adopted and a trough width parameter as K=0.3 was generally selected for the excavation in granular materials (Mair et al., 1997). The outcome showed that improvement works were necessary to reduce the risk of excessive movements and damages, as already envisaged at tender stage. Therefore a series of interventions were carried out:

– Structural works aimed at improving the building capacity to resist to the induce ground movements, i.e. to reduce its vulnerability. This included steel anchors along the bearing walls, RC works to increase strength and stiffness of the foundation, replacement of some floor slabs (SGS only partially involved);
– Ground works aimed at reducing the magnitude of the settlements and differential settlements at building foundation level by reducing the Volume Loss during the TBM excavation and therefore minimizing the ground movements. This was done by permeation grouting works, as described in the paragraph below.

5.2 *Permeation grouting*

Permeation grouting technique adopts a low pressure injection system to improve the strength and reduce the permeability of granular soils. In the present works, 100mm diameter bores are drilled into the ground to the required depth with the use of external casing in granular materials. Due to the presence of the building above the tunnel the injections points were located along the street or the courtyard and pre-excavations were often carried out to identify the location of utilities. PVC guide-pipes were therefore used to host the sleeved pipe and avoid any damage to the surrounding utilities once the area was backfilled and working platform installed.

The TAMs (high resistance PVC pipes, 27/38 mm diameter with 3 valves per meter) have been then installed and the bore is filled with a weak sheath grout. The sheath grout acts to stabilize the hole and, when set, as a blocker to prevent injection migration vertically in the bore. Finally a sliding inner injection pipe with a double packer system is pushed down inside the TAM pipe and located at the required stage level. Injection can then start and will proceed sequentially in each valve in ascending stages. When the grout is pumped, the sheath is cracked and grout spreads in the surrounding strata. Injection pressure is low to allow the grout to penetrate the soil without significantly affecting the soil structure and avoiding fracturing or claquage. Only cement-grout injections were carried out in this project with fine cement (Blaine>5000cm^2/g), additives (anti-flocculant, dispersant, fluidificant), bentonite (b/c= 0.125). The design volume of grout to be injected (150 litres/valve) and Refusal Pressure (10–12 bar) were given. However, these parameters, along with the number of simultaneous injections occurring below the same building, had to be continuously reviewed and updated following the monitoring results.

A first aim of the permeation grouting is, of course, to reduce building settlements. In particular, during the TBM excavation works the improved soil helps in reducing the soil and groundwater movements towards the face of the tunnel and radially towards the tunnel lining behind the shield and therefore in reducing the Volume Loss and ground movements at ground level. However, there is a second aim which has been pursued with the permeation grouting and which can be seen as an '*advance compensation grouting*' (in relation to the standard compensation grouting, Mair R & Hight D, 1994). In fact, although the grout is injected at low pressure, some heave can be usually observed at ground level, especially for shallow works. This should be generally limited to a minimum in order to not give disturbance/ damage to the building above. However, the heave induced during grouting works can provide an initial upwards movement which will partially/completely compensate the future settlement induced by the TBM. This is a positive effect because it increases the amount of settlements that can be tolerated by the building and, at the same time, the building will experience a smaller residual settlement in a permanent condition.

FEM analyses were carried out in PLAXIS 2D to evaluate the positive effect of the grouting intervention. An area of improved soil was modelled around the tunnel and it was seen that a reduction of Volume Loss of approx. 30% of the greenfield value was achievable. This is in line with similar evaluations carried out for the Central Line (Lunardi et al., 2014). A damage

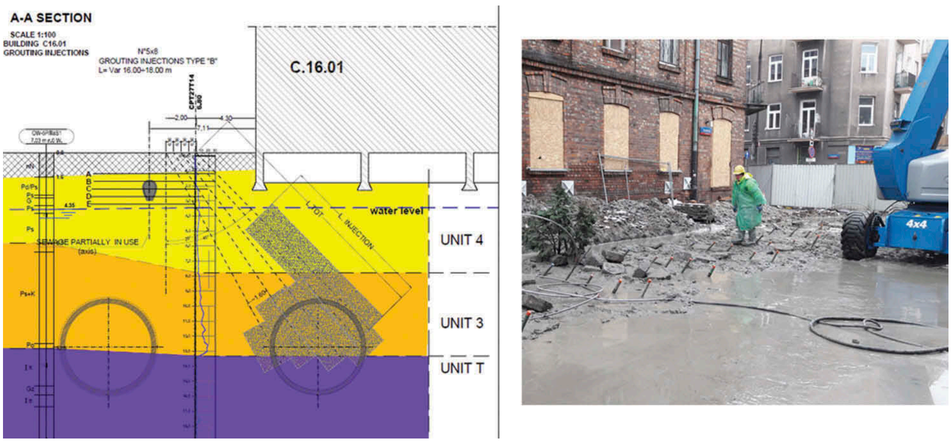

Figure 6. One of the executed soil improvement works.

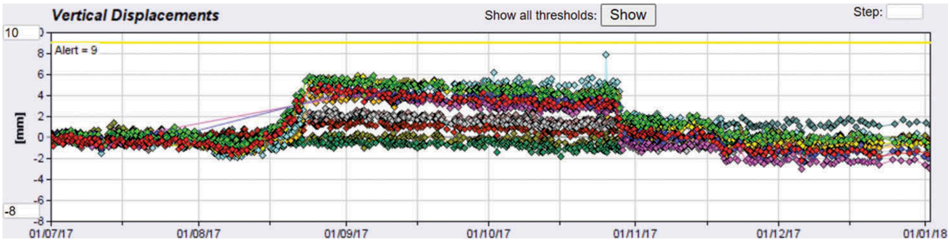

Figure 7. Vertical movements of Strzelecka Street 10 measured during injections (August 2017) and during TBM excavation (October-November 2017) through mini-prisms.

assessment showed that such reduction was sufficient to limit the expected damage within acceptable limits. Boreholes were carried out in the grouting area both before and after the grouting works. SPT tests, Le Franc tests and pressumeter tests were carried out. Comparisons of the results showed that improvement was mostly efficient in Unit 4. This could be seen: by visual inspection of the recovered soil cores; where loose sands are present, N_{SPT} showed a clear increase (N_{SPT} from 6 to 27); Menard modulus, fluage and limit pressures increased by at least 100%; permeability decreased by almost 2 orders of magnitude.

A comprehensive monitoring system was installed to verify the building response during injections and, later on, during the passage of the TBMs. This included manual readings (for ground pins, levelling pins on the building walls, crackmeters, clinometers), automatic readings (3D mini-prisms, electric crack-meters, electric clinometers) and visual observation. Therefore injections were tightly controlled in terms of grout quantity, max pressure and number of simultaneous injections in order to limit and control the building response. In certain situations, these were decreased down to 1 injection at a time and a maximum refusal pressure of 6MPa. A tight and successful collaboration was in place with the grouting Sub-Contractor (SCF).

5.3 *Results*

As discussed in section 4, the excavation in the D16 tunnel section, in particular below the historical buildings, has been successful. With regards to the buildings were soil improvement was carried out, results were satisfactory. In fact, it can be seen that for most of the cases the settlement induced by the TBMs was less than 1cm (therefore within expectations) and that the buildings raised up by the injections approximately returned to its initial level or decreased the fianl amuont of settlement. An example is the building located in 10, Strzelecka Street where monitoring results showed that it moved by the same amount (approx. 6mm) upwards during to injections and downward during the TBM excavation.

6 CASE OF TARGOWA 84 BUILDING

An interesting and delicate case is the building located at 84, Targowa Street. This is a 5-storey masonry corner building (plus basement) built in 1904. This already suffered some settlement from the excavation of C15 station (during the construction works of the Central part of Line II) and is directly above the Left Tunnel excavation. Not only, in order to safely enter the TBMs into the existing C15 station, a jet-grouting plug was foreseen to be installed adjacent to the station d-walls and hence in the immediate vicinity and even below Targowa 84 building. Therefore, a series of works have been carried out (see Figure 9):

– Jet-grouting works were carried out with extreme care with both vertical or slightly angled rods in order to improve the soil also below the building;

Figure 8. Targowa 84 building external view (left) and basement view (right).

– Permeation grouting works were carried out for the area of the building underpassed by the TBM and adjacent to the jet-grouting;
– A series of TAMs were installed and used in order to compensate any potential settlement caused by the jet-grouting works;
– A series of additional TAMs were also installed and left empty in order to have the possibility to compensate any potential settlement caused by the TBM excavation
– Strengthening of the building foundations was carried out by connecting new RC beams to the main bearing brick walls on 1-side or 2-sides of the existing footing (see Figure 10).

All these works were carried out with continous and collaborative interface among SGS, Astaldi and sub-Contractor (Keller) since the building was very sensitive to such ground works. High frequency automatic measurements and inspections within the building were done to provide an immediate feedback and adjust the grouting works in order to achieve the scope of work without inducing damage to the building.

This work was successfully completed. A pattern of building raise and settlement (due to the improvement works and TBM excavation) is visible in Figure 11. A final settlement of

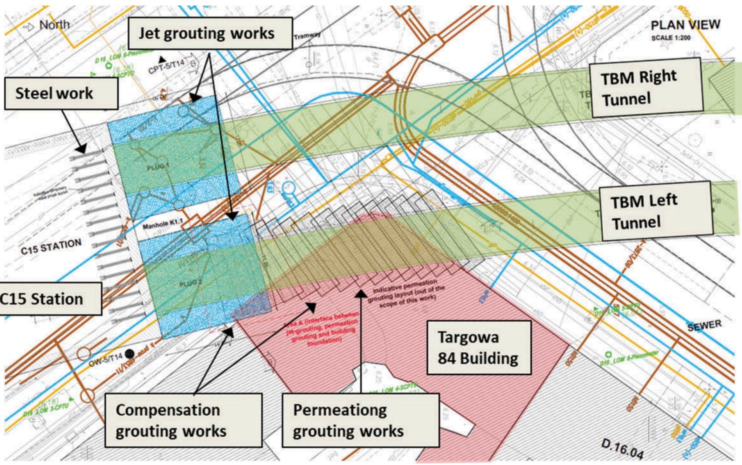

Figure 9. Plan view of the grouting works around Targowa 84 building.

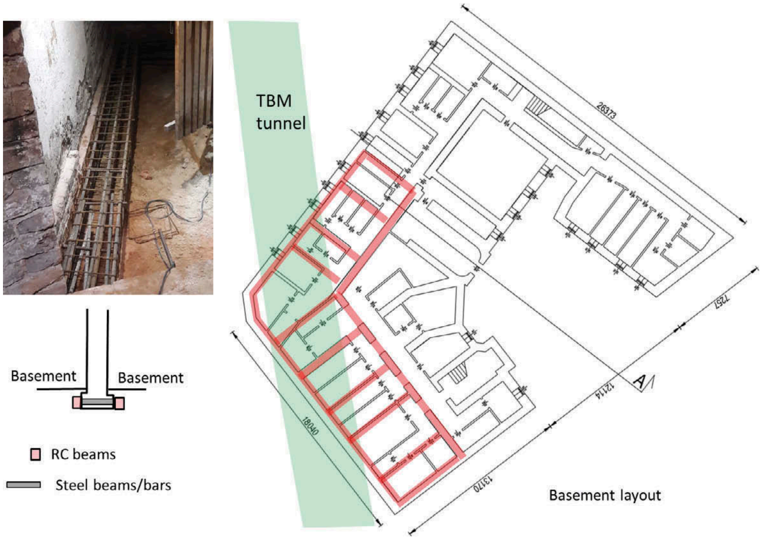

Figure 10. Strengthening works for Targowa 84 foundations.

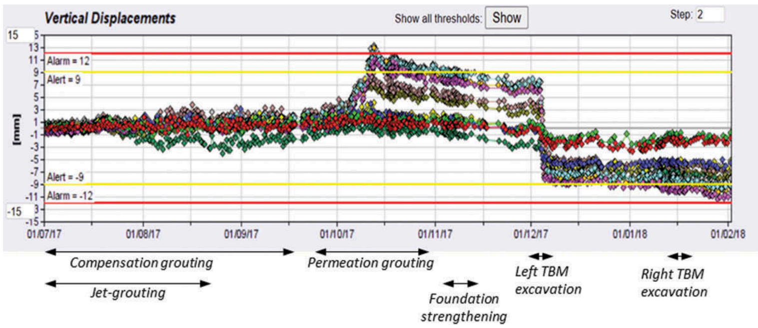

Figure 11. Measured vertical movements for Targowa 84 building.

approx. 1cm has been recorded comparing to initial status. Very minor damages with slight opening of existing cracks or formation of new small cracks have been noted within the building due to both raising and settling.

7 CONCLUSIONS

Contractor Astaldi S.p.A was appointed by the Municipality of Warsaw to execute the extension of the existing Metro Line II in Warsaw, Poland. Two tunnels were built between March 2017 and January 2018 through EPB TBMs connecting C18 and C15 stations on the area of Targowek-Praga districts. The excavation was particularly challenging due to the geological conditions (mostly sands and gravel below groundwater) and existing presence at ground level (historical buildings often in poor conditions) on D16 tunnel section. In particular for this section, the excavation was successfully completed in January 2018 with a measured Volume Loss of less than 0,3% and building settlements generally smaller than 1.0cm.

A series of improvements were done and contributed to such success. In particular, improvements were done for the TBM machine, for the advancement excavation parameters and for the materials used during the excavation At the same time in order to decrease the risk of excessive settlement and hence damage to the buildings, ground improvement was carried out in selected areas. This was done through permation grouting with the specific aim of increase the strength of the soil in front and above the TBM and also to provide an initial upwards movement to the building. This *advance compensation grouting* turned out to be very useful to limit the final settlement of the building. However, it should be remarked how an intensive monitoring system and a tight and responsive collaboration among Designer, Contractor and sub-Contractor are essential to the success of the work.

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