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The T3 stretch of Line C in Rome: TBM excavation

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ABSTRACT: Line C is the third line of Rome underground system. Two TBMs are being used to excavate the tunnels at a depth ranging from 30 to 60 m below ground level. The job sites are located in the centre of Rome, in an area characterized by several historical buildings: as a consequence, technical and operative choices have been imposed, to minimize the job sites dimension. This approach required *Metro C* to use unconventional methods to start the TBM excavation from shaft 3.3, located in the "Via Sannio gardens" very close to the Aurelian Walls at Porta Asinaria. The two TBMs were lowered into this shaft to build the two tunnels which will run as far as Amba Aradam station, over a length of about 400 m each. In order to complete the shaft itself and the tunnels to San Giovanni station, as soon as the TBMs arrive at Amba Aradam station, the TBM site equipment will be moved into this station area to complete the excavation planned for the remaining stretch. Tunneling started last March and an accurate structural and geotechnical monitoring system was installed in the soil and on the existing buildings adjacent to the line, in order to check in real time the level of interaction with the excavations.

1 INTRODUCTION

Line C is the third line of Rome underground. Once completed, it will run under the city from the South-eastern to the North-western area, for a total length of 25.6 km and 30 stations.

Metro C, the General Contractor led by Astaldi, manages the construction of Line C in all its phases: design, archaeological surveys, tunnel drilling, excavation and construction of stations, building of trains and start-up. Line C is a driverless fully automated rail system, with automatic platform doors. The automation of the system will ensure a greater frequency for the vehicles (90 seconds, theoretically) providing greater transport capacity (24,000 passengers per hour per direction). Now 22 stations and 19 km of line are open to the public.

The T3 stretch is presently under construction: it runs over a length of about 2.8 km right underneath the historic centre of Rome. The new line was divided into four different sections. The first section will link San Giovanni Station, currently in operation, to Amba Aradam Station. San Giovanni Station is an interchange between the existing line A and the new line C. At present, it is linked only to the T4 stretch of Line C, which is already in operation.

Metro C started TBM excavation from shaft 3.3, located near san Giovanni station, in the "Via Sannio gardens", very close to the Aurelian Walls at Porta Asinaria The second section of the T3 stretch will connect Amba Aradam Station to Shaft 3.2. The third section will connect this shaft to Fori Imperiali Station. The fourth section is functional to the extension to the T2 stretch, where the TBMs will stop under Via dei Fori Imperiali, waiting for the continuation of the excavations. The T3 stretch includes 2 underground stations, Amba Aradam and Fori Imperiali, and 2 ventilation shafts: shaft 3.3 and shaft 3.2. The two tunnels (Odd and Even Rail) are being bored by two Earth Pressure Balance TBMs: the tunnels have internal

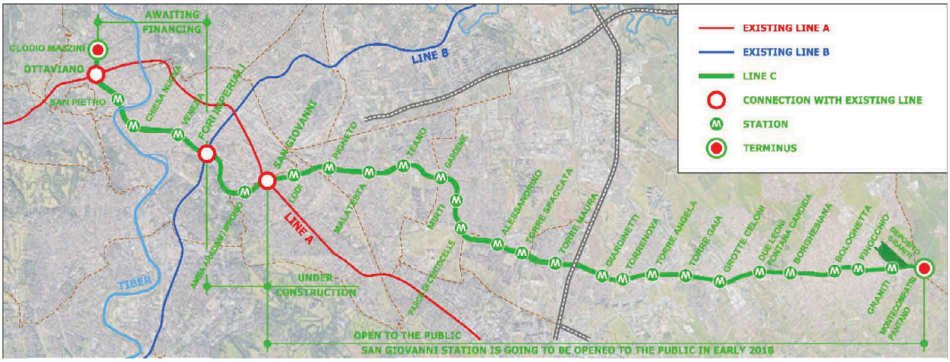

Figure 1. Line C lay-out.

Figure 2. T3 first track between shaft 3.3 and Amba Aradam Station.

diameters of 5.8 m and an external one of 6.4 m, whereas the excavation diameter is 6.71 m. The tunnels will run at a depth ranging from 30 to 60 m below ground level and they will be excavated in difficult soils. The job sites are located in the centre of Rome, in an area characterized by several historical buildings: as a consequence, technical and operative choices were imposed, to minimise the job site dimensions.

Tunnelling in the first section started in March 2018 and an accurate structural and geotechnical monitoring system was installed in the soil and on the existing buildings adjacent to the line, in order to monitor in real time the level of interaction with the excavations.

2 THE FIRST SECTION UNDER CONSTRUCTION

Design and construction were carried out applying the principles of the ADECO-RS approach (Lunardi, 2008), whose main stages are reported hereafter.

The survey phase regards the acquisition of information on the pre-existing equilibriums (characteristics of the buildings affected by the excavation, the geology and geotechnical characteristics of the soil, the natural stress-strain states, etc.).

In the diagnosis phase numerical analyses are performed, to assess the soil behaviour category depending on its response to the excavation and the level of risk associated with each building.

The therapy phase identifies the appropriate interventions (TBM parameters) which are to be implemented in order to get a category A ("stable core-face") soil response to the excavation.

The operational phase and monitoring during construction allow to continuously verify the design. In addition, appropriate adjustments are introduced, based on the monitoring of results and on the subsequent back-analysis, if necessary.

3 GROUND CONDITION

The area of the city of Rome is located on the Tyrrhenian side of the Central Apennines, where the Meso–Cenozoic carbonate rocks are covered by a succession of marine and continental Plio–Pleistocene sediments and products of the Sabatino Volcanic Apparatus and the Volcanic Apparatus of the Alban Hills. Based on the results of the surveys carried out and the general geology of the Roman area, along the route under examination the following lithological complexes have been identified, which will be excavated in the first track between Shaft 3.3 and the Amba-Aradam Station:

- Anthropogenic land complex (R)
- Complex of the Holocene deposits of the Tiber and its tributaries:
- Clayey- sandy and sandy grey-blackish silts, with variable organic content (LSO)
- Complex of the Pleistocene alluvial deposits
- Unit B of the Paleo-Tiber 2 (St)
- Unit A of the Paleo-Tiber 2 (Ar, Sg)
- Complex of the Pliocene deposits (Apl)

As regards the following tracks, the soils to be excavated are:

- Complex of the Pleistocene Volcanic deposits:
- Valle Giulia Unit (Tb)
- Pyroclastics of the volcanic system of the Alban Hills (Tl)
- Units of pyroclastic soils (Ta)

The landfills are loose, heterogeneous soils with a sandy clayey matrix and consist mainly of more or less altered pyroclastic materials reworked with fragments of stone tuffs and bricks of various sizes. The recent floods of the valley bottom consist essentially of clayey and sandy silts and medium to fine-grained, silty sands, with some gravel intercalation. The pyroclastic deposits consist of an alternation of more or less cineritic layers and of more or less cemented scoriaceous lapilli layers (Granular Tuffs). In the Pleistocene fluvial-lacustrine and fluvial-marshy sediment complex it is possible to distinguish three main horizons:

- the summit (St), consisting essentially of silty sands which fade into coarse calcareous sand with a low degree of cementation;
- the intermediate one (Ar), consisting of weakly clayey silty sands;
- the basal one (Sg) consisting of a of heterometric coarse bank gravel with a sandy matrix.
- Finally, the Pleistocene fluvial-lacustrine and fluvial-marshy sediment complex, consisting of very thick clays with frequent very thick sand intercalations.

The following tables show the geotechnical parameters adopted in the numerical analyses for each lithological unit in the first track between Shaft 3.3 and Amba Aradam Station:

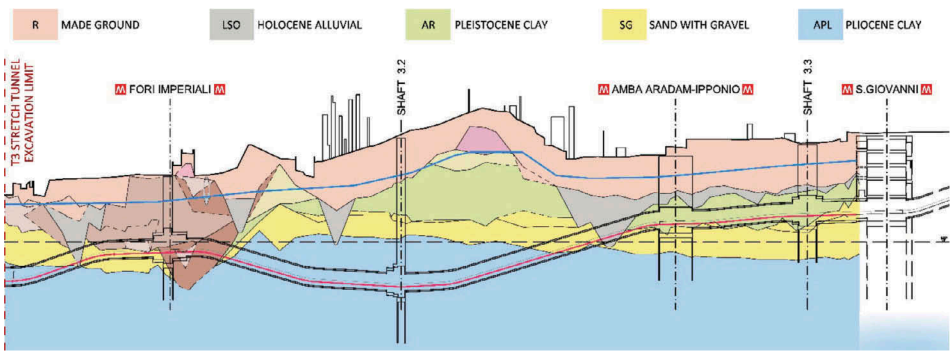

Figure 3. Geological profile of the stratch.

4 TBM EXCAVATION

The tunnels for the T3 stretch of Rome Underground will all be constructed using EPB (Earth Pressure Balance) TBMs. The final lining of the tunnel will be made of precast segments placed by the machine immediately after excavation at a small distance behind the face. The ring for the 5.8 m internal diameter tunnels consists of six 30 cm thick segments (6 + 1 keystone). In fact, the pressure exerted in the excavation chamber allows to exert the confinement pressure of the front necessary to guarantee the conditions of stability of the face in the short term and to limit the volume loss in progress, on whose extent depend the settlements generated on the surface.

The T3 section presents high ground coverings and a soil of poor geomechanical characteristics, therefore concrete segments with a characteristic strength of 50 MPa were needed. In the project the behavior of the front during the phase of excavation has been examined, identifying the range of variability of the pressure value to be maintained in the excavation chamber along the route of the tunnels, depending on the cover, the geotechnical characteristics of the land and the groundwater level.

Pressure values have been calculated by analytical methods. It is expected, throughout the phase of transit of the machine, a continuous control of the affected area, through a network **monitoring**, consisting of various types of measurement stations, located both transversally and longitudinally to the tunnel line, in order to detect movements at ground level following excursions of the pressure value at the front. Along the route some maintenance interventions will be scheduled in order to guarantee the full operation of the machine front (tool replacement, pressure sensor calibration, etc.).

Anyhow, before launching the TBM under the monuments, the machine is set up so as to reduce the time related to all operations to the minimum necessary for the excavation phases (brush maintenance, instrument calibration, extension of cables and tapes, etc.). The final lining, besides performing and ensuring the normal function of support in both the short and the long term, must also provide the required hydraulic seal.

For this reason, the segments are fitted with watertight neoprene seals along all surfaces in contact with other segments, and arranged in corresponding housings on the sides of the segment, to ensure the required water-tightness under hydrostatic pressures with the planned clamping forces. In order to ensure the water-tightness between the segments of adjacent rings, as well as for safety reasons during the transitory phases of handling and laying the segments themselves, the connection is provided by means of longitudinal mechanical dowels (Biblock System or equivalent type) arranged at regular intervals around the circumference. The TBM is equipped with 19 thrust plates arranged in groups of three for each segment plus one for the keystone, or a total of 38 jacks acting in pairs on each plate. The dimensions of the

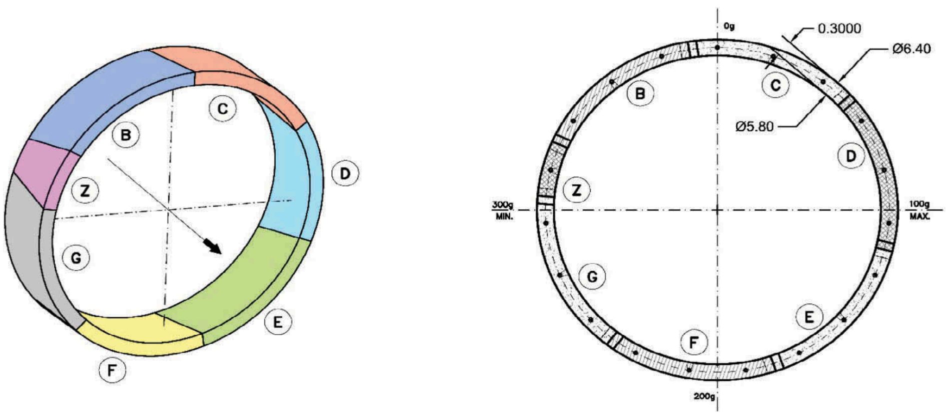

Figure 4. TBM section type: Universal ring – Particular of precast.

plate are 26 x 75 cm. The maximum thrust that the machine can exert is equal to 56,000 kN or 2,650 kN per thrust group.

5 TBM JOBSITE AND CONSTRUCTION PHASES

The peculiar urban environment in which the jobsites of the T3 stretch are located required the reduction of their sizes as much as possible, with significant consequences on the design and operational choices, in particular those related to the TBM excavation of the tunnels.

The launching shaft of the TBMs, called Shaft 3.3, is located in the Via Sannio gardens. Starting from that shaft, the gallery stretch up to the Amba Aradam – Ipponio station was constructed, for a length of about 385 each.

Once completed this gallery track, the TBM jobsite will be relocated to the Amba Aradam station to complete the mechanised excavation as far as the end of the stretch, for a total length of about 2.4 km for each direction, whereas the shaft and the galleries which extend up to the San Giovanni station will be completed by a traditional excavation.

The Via Sannio shaft is 62 m long and 22 m large: it is totally undersized as compared to those generally needed to enable the operation of these TBMs, which are equipped with a 100 m back-up. Moreover, at the same time as the excavation of the 2 TBM galleries, consolidation work of two 150 m long microtunnels was carried out, heading for the line stretch already in operation, starting from the same shaft.

The 2 TBMs (of about 450 tons each) were entirely assembled on the surface and lowered through a temporary slot down to the bottom of the shaft by a superlift Liebherr LG1750 750-ton lattice boom crane. Once laid on purpose-built steel structures, placed at the bottom of the shaft, the TBMs were moved as far as the head diaphragm wall to start the excavation.

Two false tunnels for the launch of the TBMs were constructed in shaft 3.3. These structures must be able to create an adequate confinement for the TBM head in order to reach the designed support pressure in the first meters of excavation outside the station, until the first ring is placed and backfilled in correspondence to the station wall. Before the TBM arrival, the lower part of the cradle is cast and anchored to the bottom slab and the reinforcement in the area between the wall and the TBM. When the TBM arrives, all the reinforcement bars can be mounted around the TBM and then the false tunnel is cast, protecting the station wall and the TBM shield with polystyrene pads. After the passage of the TBM back-up, the false tunnel structure will be demolished and the slab completed with an integrative casting until the final level.

In order to enble the operation of the machine, (350 m^3) slurry tanks were constructed at ground level. On the shaft, **a** 35 +38 tons Goliath crane was installed, dedicated both to the feed of the equipment needed for the excavation (precast segments, rails, pipelines, lubrication and sealing means, etc.) and to the extraction of the spoil.

The dimensions of the shaft also required to:

- start the excavation with only 4 out of 7 muck cars installed at the rear of the TBM;

Figure 5. TBM job site in shaft 3.3.

Figure 6. Archaeological remains in Amba Aradam Station.

- up to the (15th thrust, the excavation was performed by unloading the conveyor belt through a transverse conveyor on a car powered by a locomotive at the bottom of the shaft on a track adjacent to the TBM. The spoil car was equipped with bits, needed to extract it (through the central slot of the shaft) and unload it in the slurry tank through one of the two winches of the Goliath crane;
- up to the 35th thrust, once cleared the bottom of the central slot with the fourth car, it was possible to place the spoil car and add another car, at the rear of the TBM.
- starting from the 66th thrust, it was possible to complete the back-up of the TBM with the last 3 cars. By assembling also an elevated single switch at the tunnel mouth, it was possible to complete the final configuration for the excavation up to Amba Aradam station placing the back-up with a locomotive and 4 spoil cars, as well as another power unit car, precast segments and spoil cars.

Once completed the excavation of the first gallery, the second was started, with the same methodology and operative timing.

In order to respect the construction timing of the launching station (Amba Aradam), which was involved in important archaeological findings, both the TBMs accessed the area before the excavation had reached the foundation slab.

6 INTERACTION EVALUATIONS WITH EXISTING BUILDINGS

The hazards associated with the tunnel construction in urban areas include poor ground conditions, presence of a water table above the tunnel, shallow overburden (20m) and ground settlements induced by tunneling, with potential damage to the existing structures and utilities above the tunnel. In the case of the T3 stretch of Rome Underground a study to assess the interference between underground excavations and the existing buildings was carried out. The excavation is performed by a mechanized system, by means of an EPB type TBM. The subsidence trough related to the excavations have been evaluated, to assess the expected damage class for each building. Three stage of analyses should be considered:

- Empirical evaluation of settlement, which defines the subsidence basin with Dependent Gaussian on the Lost volume functions (Peck, 1969; O'Reilly and New 1982), has been carried out ("green field" analyses). As a result of the evaluation of the subsidence basin and of the surface and foundation level settlements, the effects induced on the buildings were evaluated by calculating the damage categories as reported in the literature (Mair et al., 1996). The envelope of the area affected by the deformations is therefore the function of the distance from the vertical axis of the tunnels and depends on the size of the tunnels, their dimension, the lost volume and the resistance and deformation parameters of the excavated ground.
- Settlement analysis by FDM analyses were performed only for the most significant cases (historical buildings), where the interference problem is more severe; so, a more reliable

prediction of the ground deformation response is achieved, taking into account the interaction with the building.
- A 3D Model was implemented only for the critical cases (historical buildings), taking into account the real geometry and the structural-construction system of the interference.

7 DIAGNOSIS PHASE – BUILDING RISK ASSESSMENT IN THE CURRENT SECTION

In the analysis of the excavation, the shape parameters of the Gaussian curve k=0.4 were assumed; the maximum volume loss is 0.5%. The following table shows the results of the analysis carried out in the current stretch. The damage criterion used for Line C provides two main categories (depending on the information deduced from technical datasheets) for the buildings:

- Category A: ordinary buildings with no previous structural damages
- Category B: ordinary buildings with previous structural damages and/or sensitive sites (school, hospital, offices)

Since settlement profile was produced at the foundations level, building risk assessment at this stage was carried out, in compliance with Burland & Wroth's theory (equivalent simple beam), calculating the maximum tensile strains induced by tunnelling. It is possible to define the following block diagram (Unified criteria for tunnelling induced damage assessment):

- Category A (ordinary buildings with no previous structural damages)

Settlement prediction in free-field condition with empirical methods
Damage assessment (Burland & Wroth, 1974)

- Category of damage equal/lower than 1 → no protective measures
- Category of damage higher than 1 → protective measures
- Category B (ordinary buildings with previous structural damages and/or sensitive sites)

Settlement prediction in free-field condition with empirical methods:

- $W_{max} \leq$ 5mm OR 5mm < W_{max} <10mm and $\beta \leq 1/1000$ → no protective measures
- $W_{max} \leq$ 10mm OR 5mm < W_{max} <10mm and $\beta \leq 1/1000$ → no protective measures

8 MONITORING SYSTEM

A fundamental aspect of tunnel construction in urban areas is the control of subsidence induced by excavation, which is directly proportional to the volume loss values. The subsidence that occurs at the surface is, in fact, due to the deformation behavior of the core-face and the convergence values at the face, along the shield and in the area in which the precast segments are installed and grouted. If applied properly, the EPB technology can minimize the subsidence induced at ground level, in a manner which is compatible with the urban environment and the shallow overburden in some parts of the route. Controlling the pressure at the face, as well as the grouting pressures, allows for a careful construction; besides, the volume of grout mix injected behind the segments are of primary importance in limiting the volume loss. Correctly controlled tunnelling thus allows to keep under control the volume loss during excavation, and hence the predicted subsidence on the surface. Surface monitoring is primarily concerned with the buildings and their foundations, monuments and their foundations, the land on which these buildings are situated, and their variations in terms of geotechnical and hydro-geological characteristics.

- **External monitoring:** several ground settlement measurements are considered, through levelling pins, inclinometers (horizontal displacement), extensometer (vertical displacement) and vibrating-wire piezometer (water table movement).

- **Internal monitoring:** it checks correspondence between design analysis and in situ measurements, in order to ensure precast segmental lining to work properly. Stress state of tunnel lining had to be monitored by vibrating-wire strain gauges BE/BC, lining convergences and diametrical distortion by optical levelling MP (targets and prisms). TBM parameters (face pressure, volume of the excavated material, advancing rate) had to be monitored.

The control system considers several sections, perpendicular to the tunnel axis, provided by surface and internal instrumentation.

- The topographic monitoring sections (MON-02 ÷ MON-07) provide for the monitoring of the ground level (topographic monitoring). It consists in the installation of no 9–11 levelling pins installed at ground level, aligned perpendicular to the tunnel axis.
  - The geotechnical monitoring sections (MON-01) provide for the monitoring of the ground level (topographic monitoring), the stress-strain behavior of the ground (geotechnical monitoring) and the stress-deformation state of the lining (structural monitoring). It consists in the installation of the following:

    i. no 10 levelling pins installed at ground level, aligned perpendicular to the tunnel axis;
    ii. no 3 inclinometers, 2 of which external to the excavation area and 1 along the tunnel axis;
    iii. no 2 boreholes, external to the excavation area, each with 2 vibrating-wire piezometers (the one for the surface water table and the other for the possible deep water table);
    iv. no 2 extensometers, installed along tunnel axes, whose depth depends on the tunnel cover;
    v. no 10 mini-prisms, anchored to the tunnel lining: 5 within ring 116-Odd Track line and 5 within ring 12-Even Track line (pentagonal arrangement);
    vi. no 84 VW strain-gauges, for monitoring the stress state in the lining, within ring 116-Odd Track line and ring 12-Even Track line.

Mini-prisms, data-loggers and VW strain gauges identify the position of the instrumented rings (ring 116 for the Odd Track line and ring 12 for the Even Track line). In order to better define the stress-state in the ground around the tunnel in free-field condition, a further monitoring section was suggested:

- The special monitoring section (MON-05 "Campo Romulea") provides for the monitoring of the ground level (topographic monitoring) and the stress-strain behavior of the ground (geotechnical monitoring). It consists in the installation of following:

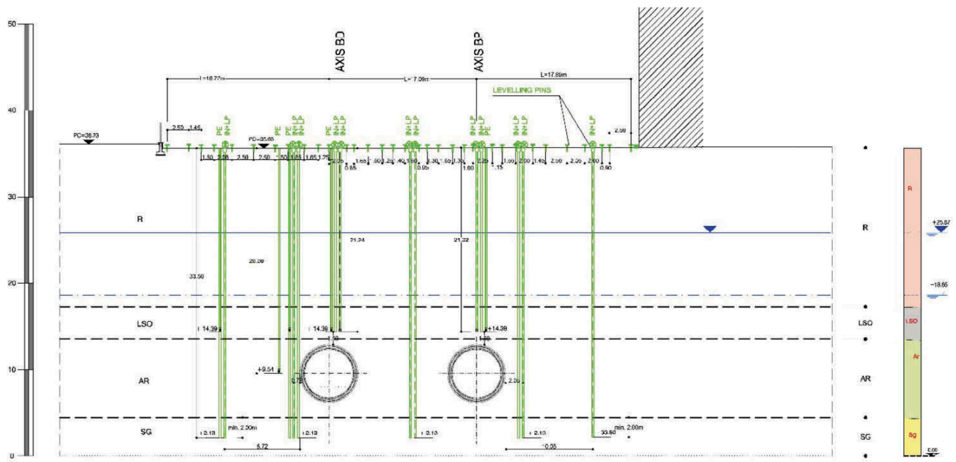

Figure 7. MON 05: Monitoring section.

i. no 33 levelling pins installed at ground level, aligned perpendicular to the tunnel axis;
ii. no 5 inclinometers, with mini-prisms at the top;
iii. no 5 boreholes, external to the excavation area, with 2 vibrating-wire piezometers each (the one for the surface water table and the other for the possible deep water table);
iv. no 7 extensometers, with mini-prisms at the top.

The subsidence analysis is intended to provide a prediction of the subsidence values, which will be determined in compliance with threshold values. In particular, "warning" (80% of expected settlement, that is 9.2 mm) and "alarm" (100% of expected settlement, that is 11.5 mm) thresholds are identified, defined along tunnel axis in free field conditions. It is provided that also the parameters of the TBM excavations must be continuously monitored and compared to the design values.

9 BACK ANALYSIS – ODD TRACK SECTION ALREADY EXCAVATED

In order to calibrate the design parameter in the design range of variability and to monitor the excavation, the data are automatically recorded by the TBMs and processed in real time. In this case, the TBM face design pressure had provided limited values in terms of settlements and volume loss, in accordance with the threshold limits suggested. The following pictures show a comparison between the monitored settlement profile and the design settlement profile along the Odd Track line monitoring section.

As shown in previous figures, the design parameters had been correctly defined. The Volume loss can be assessed as 0.3–0.4%, while k=0.4–0.45 for most of sections; these values are close to the design parameters (V_L=0.5%, k=0.4). So, the design methods and assumptions were confirmed and so they were used to contain settlements and volume loss within the thresholds for the Even Track as well.

10 TBM ADVANCING DESIGN PARAMETERS – ODD TRACK LINE

The main parameters defined in the design and monitored during construction were those related to the pressure stabilization in the excavation chamber and the backfill pressure of the grout injections behind the concrete segments. The results of the monitoring were used to carry out numerical back analyses continuously, which made it possible to check the design machine parameters in real time and promptly take appropriate corrective action in order to conform to the safety requirements.

Pressure at the face: the pressure at the face and at tunnel contour were analysed and defined, in order to keep the loss volume within the design limit. In this case the design and

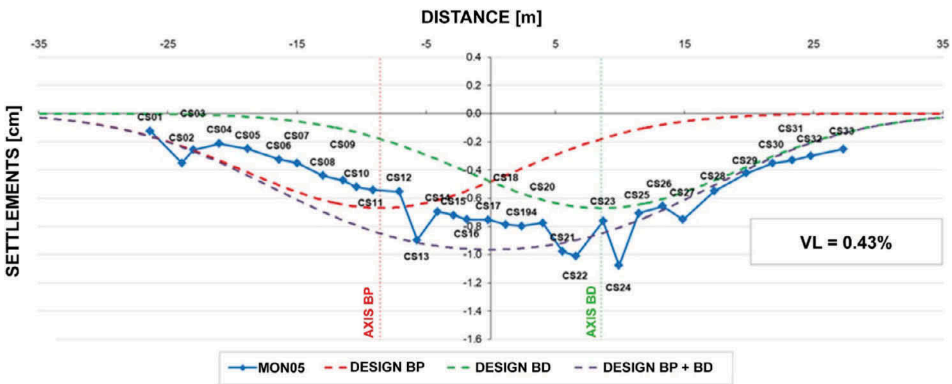

Figure 8. MON 05: Transverse profile of settlements.

back analyses confirmed that this pressure is between the condition of active pressure (Rankin formulation) and at-rest pressure.

Grout injection pressure at the back of the TBM shield, to fill the voids between the precast segment lining and the excavation, was estimated according to front pressure, increasing it by 0.5-1bar. This value must be controlled, in order to prevent high pressure. Back-filling pressure must not overcome the average in-situ lithostatic stress.

Grouting injection volume: In order to control the balance between the tunnel volume, the volume of excavated material and the grouting volume, the weight of the excavated material was assessed. The grouting volume was assessed as the difference between the excavation volume (related to Ø=6.71m) and the extrados ring volume (related to Ø=6.40m). For each advancement (1.4m), equal to a single ring length, the design volume to be injected is 4.47m^3

Weight of the excavated material: In order to control the balance between the tunnel volume, the volume of the excavated material and the grouting volume, the weight of the excavated material was assessed. The weight of the excavated soil corresponds to the volume of each advancement (1.4m) multiplied by the weight per unit volume of the excavated material (expected 20 kN/m^3).

11 THE TBM ADVANCE DATA – ODD TRACK LINE

The analysis concerning the TBM data consisted in the registration of all TBM parameters and in their subsequent summarization. The data described above were summarized for each thrust and compared to the design value in term of: earth pressure, grouting volume, grouting pressure, volume of excavated material. Furthermore, in order to keep the thrust under control, other parameters were checked: speed and torque, force main thrust, advance speed. The following figures summarize the face support pressure values recorded by the sensors of the TBM, during the track tunnel excavation. The volume of the excavated material was controlled through the weighting of the muck extracted during the excavation. According to the TBM data recorded, the following can be established:

- The average face pressure are consistent with the design range within the defined track, with only a distortion between central sensors
- The back-filling injection pressures are oscillating, with an average value in accordance with design parameters

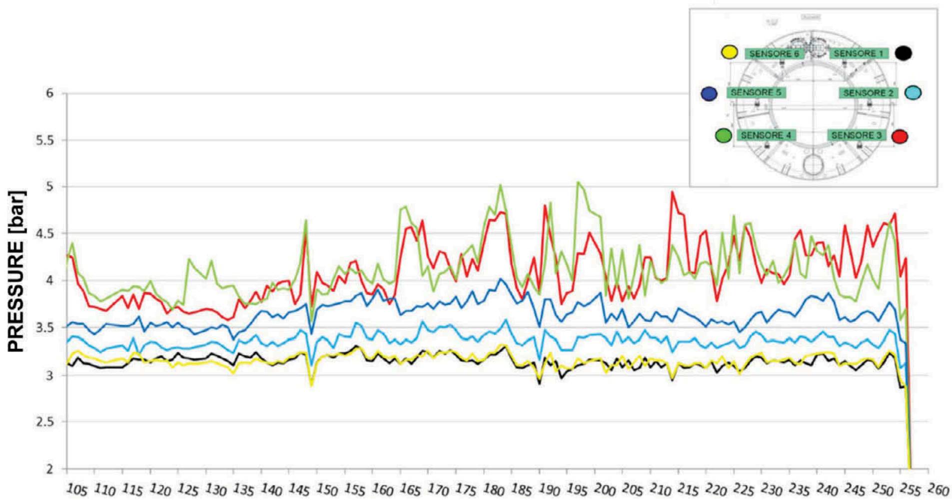

Figure 9. Earth pressure balance.

- The weight of the extracted material appears to be constant and in accordance with the design value
- The back-filling injection volume appears to be slightly higher than the design value (about 20%). This value must absolutely be expected, due to the continuous maintenance

The other TBM parameters (torque and main thrust force) are consistent with the expected values.

REFERENCES

Boscardin, M. D., et al. 1989. *Building response to excavation induced settlement*; Journal of Geotechnical Engineer ing, ASCE, 1.

Lunardi, P., 2008. *Design and Construction of Tunnels. Analysis of Controlled Deformation in Rock and Soils (ADECO-RS)*. Springer, Berlin, Germany.

Mair, R. J., et al. 1996. *Prediction of ground movements and assessment of risk of building damage due to bored tunneling*.

O'Really, M. P., et al., 1982. *Settlement above ls in the United Kingdom – their magnitude and prediction*; *Proceedings of Tunneling Symposium 1982*

Peck, R. B., 1969. *Deep excavations and tunneling in soft ground*; *Proceedings of 7th International Conference on Soil Mechanics and Foundation Engineering*. Mexico City