Milan ligne 4: Traversée Est-Ouest sous le centre-ville

Milan line 4: from east to west crossing the downtown

Abstract
La ligne M4, en construction depuis 2013, jouera un rôle clé dans le système de transport à Milan, qui vise à intégrer le système de lignes de métro, avec le rail et les aéroports. La nouvelle ligne de métro passera par Milan avec une longueur de 15 km d'ouest en est. La Ligne M4 sera un "métro légèr entièrement automatisé ", sans chauffeur et un système de signalisation CBTC. Les intersections de la M4 avec le système de transport éxistant, sont fournis avec la M1 (gare de S. Babila) et M2 (gare de S.Ambrogio) et les lignes de chemin de fer de banlieue: S5, S6 et S9 à la gare de Forlanini et S9 la gare de San Cristoforo, une liason est également prévue près de l'aéroport de Linate.

L'utilisation de l'excavation mécanisée et le choix d'un modèle à voie unique et double galerie a été fait pour assurer la flexibilité et l'adaptabilité de la route. Pour la réalisation des galeries est prévu l'utilisation de six EPB-TBM, quatre avec un diamètre d'environ 6,5 m, pour les sections extérieures au centre et deux sections avec un diamètre de 9,15 m pour le centre, qui devrait également contenir les quais de la gare. Pour les stations sont prévues des structures de soutien jusqu'à 46 m de profondité et d'interventions massives de consolidation du sol au moyen d'injections, pour permettre l'application de méthodes d'excavation bottom-up et top-down. L'article décrit l'approche de la conception et les systèmes constructifs utilisés pour les tunnels et les gares, qui varient selon le tissu urbain traversé, et les pré-existantes, et aussi les éléments de preuve sur les données recueillies depuis le début des travaux à ce jour.

Abstract:

The Line M4, under construction since 2013, will play a fundamental rule for the Milan Transport Integrate System which connects Metro System, Railway System and Airports. The new metro line will cross Milan with a length of 15 km from west to east along Viale Lorenteggio, passing in the south part of the old town and along the axes of Indipendenza, Argonne and Forlanini up to Linate Airport. Line M4 will be a “fully automated light rail” system, driverless and a CBTC (Communication Based Train Control) signalling system. The line interchanges with existing Metro M1 (S.Babila station) and M2 (S.Ambrogio station) and with suburban railway lines: S5, S6 and S9 at Forlanini station and S9 at San Cristoforo station, over the Linate Airport.

The extensive use of mechanized tunnelling and the selection of a single-track twin tunnel layout help maximize the flexibility and adaptability of the route, which is situated entirely underground except for the depot/office area. The running tunnels will be bored using six EPB-TBMs, four with diameters of about 6.5 m for the sections outside the downtown and two with 9.15 m diameter for the downtown, containing the station platforms too. For stations, retaining walls up to 46 m depth and extensive grouting treatment will be executed, providing top-down and bottom-up construction systems. The paper describes the design and construction approach adopted to tunnels and stations depending on the urban fabric, the overburden and the preexistings, and the evidence collected during construction works up today.

Milan ligne 4: est en ouest en traversant le centre

Milan line 4: from east to west crossing the downtown

Giuseppe LUNARDI, *Rocksoil S.p.A, Milan, Italy*

Giovanna CASSANI, *Rocksoil S.p.A, Milan, Italy*

Martino GATTI, *Rocksoil S.p.A, Milan, Italy*

Stefano GAZZOLA, *Rocksoil S.p.A, Milan, Italy*

1 Introduction

The construction of the new M4 (blue) line, managed according to the project finance formula, has been divided into three different sections. The first section will link Milan Linate airport to the Forlanini railway station and then to the Tricolore Station. The second section will connect the Tricolore Station to Parco Solari Station. The third section will connect San Cristoforo railway stations to section two. The new metro line will link the eastern and western parts of the city and its construction will be completed by 2020. The line has altogether 21 underground stations and will have a total length of 14.2 km. The running tunnels will be bored using six EPB TBMs: 4 TBM for the two single-track tunnels with diameters of 6.5 m for the sections outside the city centre (2 from east and 2 from west). The central part of the track, however, will be constructed using two 9.15 m diameter EPB TBMs to include the platform for the subway stations.

Rocksoil taken on the responsibility of: geological, hydrogeological and geotechnical characterization of the metro line alignment; detailed design of the running tunnels driven by TBM and connection way; evaluation of subsidence induced by tunnel excavation and Building Risk Assessment; design of the monitoring system. Rocksoil designed also the 6 deepest stations (from S. Ambrogio to San Babila) and ground improvement intervention related to: TBM break-in and break-out in correspondence of the station, by pass and connection way to inter-line structures excavated by conventional excavation method. Civil Works are performing by Salini-Impregilo S.p.A and Astaldi S.p.A..

2 The project

Line M4 will cross Milan with a length of about 15 km from west to east along Viale Lorenteggio, passing south of the old town and along the axes of Indipendenza, Argonne and Forlanini up to Linate Airport. The M4 route will optimize city coverage, loading options, and interconnection with the metro and suburban rail network, thereby improving the overall network effect of the entire public transport system in the city.

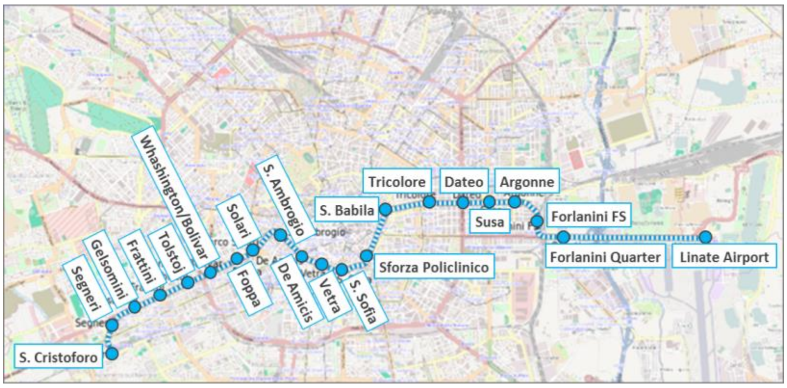


Figure 1. Metro Line 4 Layout

Line M4 will be a “fully automated light rail” system, driverless, and with automatic platform doors and a CBTC (Communication Based Train Control) signalling system. The trains will be 50 m long, considerably shorter than rolling stock in circulation today. Likewise, the 50 m long stations will also be shorter than the 110 m stations on lines M1, M2 and M3. The relatively compact dimensioning of the structures, particularly the stations, means that construction work on the line can be carried out more easily and with less impact. The automation of the system will ensure higher frequencies for the vehicles (90 seconds, theoretically reducible down to 75) providing the capacity to transport 24,000 to

28,000 passengers per hour per direction. The new line M4 will pass through neighbourhoods with high population densities, so the construction methods have been planned to minimize impact at the surface and adapt to an underground affected by a great amount of infrastructure and by the presence of a significant amount of water. The extensive use of mechanized tunnelling, and the selection of a single-track twin tunnel layout help maximize the flexibility and adaptability of the route, which is situated entirely underground except for the depot/office area.There are currently two interchanges with existing Metro lines, one with the red line at San Babila station, and one with the green line at S. Ambrogio station. In the future, there will be three interchanges with suburban railway lines, one with Lines S5, S6 and S9 at Forlanini FS station, one with Lines S1, S2, S5, S6, S13 at Dateo station, and one with Line S9 at San Cristoforo station, where there is also a connection to the Milan-Mortara railway. Lastly, an interchange with Linate airport is planned.

Most of the underground construction on the route will be carried out by mechanized tunnelling with the use of two TBM geometries, one with a bored diameter of 9.15 m and the other with a bored diameter of approximately 6.36 m.The TBMs with diameters of approximately 6.36 m will be used for the sections from Manufatto Ronchetto, in the San Cristoforo area, to the Parco Solari station and from Linate Airport to the Tricolore station. The TBM with a diameter of 9.15 m will be used for the section from the Parco Solari to the Tricolore station. As indicated, the machine with a diameter of 9.15 m will be used in the section through the deep stations in the historic centre in order to enable the installation of the station platforms directly inside the inner contour of the tunnel in segments. This allows a considerable reduction of the impact on existing structures compared to the use of conventional methods of tunnel excavation, after performing consolidation work.

Design and construction was carried applying the principles of the ADECO-RS approach (Lunardi, 2008), following are reported its main stages. The survey phase regards acquisition of information on the pre-existing equilibriums (characteristics of the buildings affected by excavation, the geology and geotechnical characteristics of the ground, the natural stress-strain states, etc.).The diagnosis phase in which numerical analyses are conducted to assess the behaviour category of the ground's response to the action of excavation and the level of risk associated with each building. The therapy phase identifies the properly interventions (TBM parameters) which are necessary to apply in order to have a ground's response to excavation in category A (stable core-face). The operational phase and monitoring during construction allows verifying continuously the design. In addition, appropriate adjustments are introduced, based on the monitoring results and on the consequent back-analysis, if it is necessary.

2.1 Running Tunnels

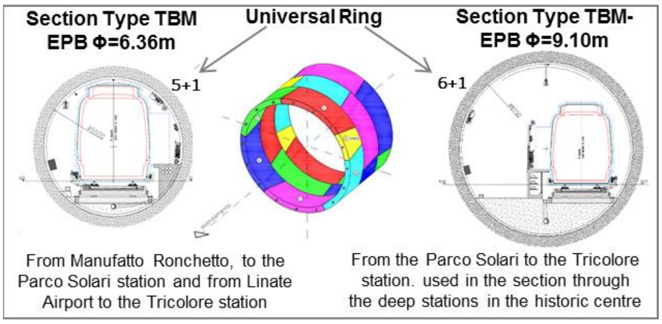
The running tunnels for Line M4 of the Milan Metro will all be constructed using EPB (Earth Pressure Balance) TBMs. The final lining of the tunnel will be made of precast segments placed by the machine immediately after excavation at a small distance behind the face. The ring for the 6.36 m diameter tunnels is composed of six segments (5 + 1 keystone) with a thickness of 28 cm. That of the 9.15 m tunnel is composed of seven segments (6 + 1 keystone) with a thickness of 35 cm (Figure 2.a).

The final lining, in addition to performing and ensuring the normal function of support in both the short and 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 water-tightness between the segments of adjacent rings, as well as for reasons of safety 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 6.36 m TBM is equipped with 16 thrust plates arranged in groups of three for each segment plus one for the keystone, or a total of 32 jacks acting in pairs on each plate. The dimensions of the plate are 26 x 70 cm. The maximum thrust that the machine can exert is equal to 42,575 kN or 2,660 kN per thrust group (Figure 2.b). The 9.15 m 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 plate are 33 x 100 cm. The maximum thrust force that the machine can exert is equal to 81,895 kN or 4,310 kN per thrust group.

2.2 Station

For the construction of stations and structures, the planners tried to resort as much as possible to the open excavation method supported by reinforced concrete diaphragm walls (open bottom-up method), which is compatible with the existing road network and construction site areas required for the execution of the works. This type of construction is applicable in the Linate–San Babila axis since the bodies of the stations are manufactured within the central parterre of the boulevards, minimizing interference with road traffic while providing sufficient construction site areas. The same type of construction will also be used for the stations on the San Cristoforo–Parco Solari section, with the exception of Gelsomini and Segneri stations, for which totally or partially closed bottom-up methodology is planned.

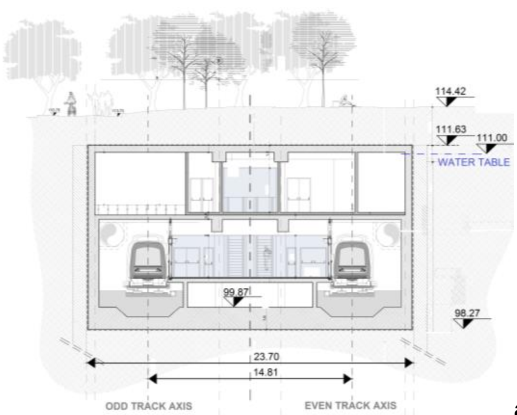


a)

b)

Figure 2. a) TBM Sections type; b) Forlanini Railway Station – TBM breakthrough odd track

The Line 4 stations, with the exception of those in the central section, generally have a limited depth of about 15 m, through which the two TBMs pass "unloaded". The level of the floor slab thus remains occupied by the TBM supply site comprising the rails for trains transporting precast segments, conveyor for transporting the muck out of the tunnel, hoses for cooling water and a medium voltage cable for the TBM power supply, for each of the two machines (Figure 3.a-b). The use of semi-precast self-supporting structures is planned constructing the horizontal elements of the station. The supporting structures for the excavations, bulkheads, tie rods, and bottom sealing blocks, will be installed by means of clamshell excavation and stabilized with bentonite slurry, tied with anchors outside the aquifer and bored without the use of a preventer and bottom buffers in integrated cement injections. The stations considered as "deep" are Sant'Ambrogio (Figure 4.a), De Amicis, Vetra, Santa Sofia, Sforza Policlinico and San Babila. The functional installation is composed of a central shaft with an excavation depth up to approximately 30 m and transverse dimensions limited to approximately 10 m. Outside this, running tunnels are constructed using a TBM with 9.15 m diameter, which is sufficient to accommodate the platforms of the stations. The station have been excavated by means of lateral retaining walls, represented by RC diaphragm, supported by anchor or steel frame (locally by slabs, for top-down system) and with a grouted plug at the base able to prevent water inflow. This plug for the deep stations are pushed to a consistent depth below the bottom of the excavation, up to 16–17 m, bringing the total length of the retaining walls up to approximately 50 m, with a lot of construction problems (connections for reinforced cages, amount of reinforcement, Figure 4.b). The connecting bypass between the station shaft and the platforms will be excavated after the soil has been grouted from ground level with the continual use of cement and silicate mixes.



a)

b)

Figure 3. Argonne Station: a) Detail of the reinforced concrete piling; b) general view

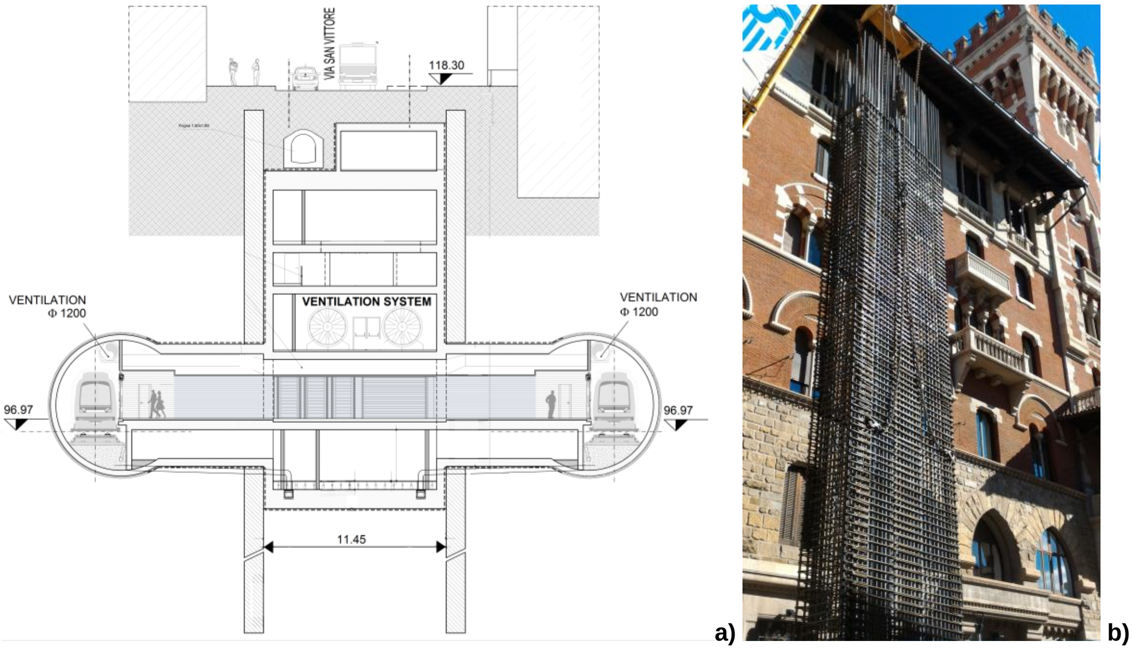


Figure 4. a) Sant'Ambrogio deep station – interconnection with Line 2; b) detail of the reinforced cage

The project included an analysis of the interference between the excavations of the running tunnels with the surface buildings and structures. The subsidence basin were evaluated in detail relatively to the excavation. Furthermore, the subsidence/displacements were determined at ground level as well as at the level of the foundation, assessing the damage class expected for each building. In subsequent stages of the project, on the one hand, the interference analysis will be more highly developed with numerical analysis methods, and on the other hand, the detailed findings for some of the buildings in the area of the subsidence trough will be completed.

3 Interference

The hazards associated with the tunnel construction in urban areas include poor ground conditions, presence of water table above the tunnel, shallow overburden and ground settlements induced by tunnelling with potential damage to the existing structures and utilities above the tunnel. A fundamental aspect of metro line design is the evaluation of the excavation interference (Cassani et al. 2005; Mancinelli et al. 2009). In case of M4 metro line a study to assess the interference between underground excavations and the existing buildings has been developed. The excavation takes place with a mechanized system, adopting an EPB type TBM. The subsidence basins and the settlements related to the excavations have been evaluated to assess the expected damage class for each building.

Three stage of analyses have been considered: 1) empirical evaluation of settlement, according to "empirical formulations", which define the subsidence basin (Figure 5) with Gaussian-scale dependent on the Lost volume functions (Peck, 1969; O'Reilly and New 1982) has been defined ("green field" analyses). As a result of the subsidence basin definition and surface and foundation level settlements the induced effect on the building have been 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 itself, its dimension, the lost volume and resistance & deformation parameters of the excavated ground. 2) Refined analyses of the settlement, by FEM or FDM analyses, have been performed for the most significant cases, where the interference problem is more severe; so a more reliable prediction of ground deformation response is achieved, taking into account the presence of the buildings' foundations. 3) Finally, for the critical cases, a 3D Model for building has been implemented, taking into account the real geometry and structural-construction system of the interference. For the first two stage, the damage analysis has been performed by the approach reported in 3.1.; for the third stage, the 3D model is able to give a direct response about cracks and damage situations.

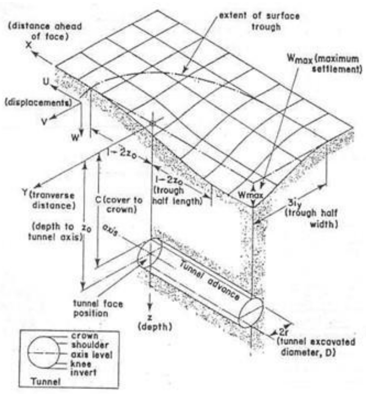


Figure 5. Theoretical definition of subsidence basin

3.1 Building risk assessment

On the basis of experimental data, Boscardin & Cording (1989) correlated the expected damage to buildings with the values for the resistance to cracking of the materials on a scale of between 0 (negligible damage) to 5 (severe damage). Risk analyses developed on the basis of the classic theories produced the results reported in the tables 1. In case of M4 the analysis have been performed considering a coefficient k, which is basically a function of the nature of the ground to be excavated, equal to 0.35 and volume loss equal to 0.5% and 0,7% (worst credible scenario).
The performed analysis shown that settlements due to mechanized excavation (Figure 6.a) do not result in specific risk conditions. Anyway, in order to define the risk levels, both numerical analyses were developed using the Itasca FLAC finite differences calculation programme (Stage 2) and empirical methods derived from the classic theories listed previously:

- the theoretical reduction in the volume of ground lost was assessed using the FLAC analyses and empirical methods;
- once the expected values for lost volumes were known, the risk analyses were carried again out using the same criteria as those reported in section 3.

Simulations of the different stages of tunnel excavation (Figure 6.b) were carried out using two dimensional FLAC analysis (Fig.6.c), replacing the ground excavated with equivalent forces, which were gradually reduced as a percentage to reproduce the effect of tunnel advance. The first numerical step was to calculate the percentage reduction of the excavation forces under green field conditions and in the absence of buildings, in order to obtain the congruence between the theoretical subsidence curves (V_L=0.50% and V_L=0.70%%), obtained using classical methods and that calculated by using FLAC iteration analyses (Figures 6.d).

Table 1 - Damage Classification – Interference A20

Interference	Section	Foundation Level Overburden [m]	Specific case	Building Max Settlement [mm]	Hogging ε_{max}	Sagging ε_{max}	Damage Class
A20	Folanini Quarter Forlanini Railway Station	9,5	Even Track - V_L=0,5%	14,3	0,047%	0,061%	1
			Even Track - V_L=0,7%	20	0,066%	0,085%	2
			Odd Track - V_L=0,5%	10,5	0,042%	0,001%	0
			Odd Track - V_L=0,7%	14,6	0,059%	0,012%	1

The analyses were then carried out in the presence of buildings via 3D model (Figure 7), with the percentages of the excavation forces determined in this manner. Finally, the percentages of the volume of ground lost were determined in the presence of building, comparing the subsidence depression calculated using those analyses with those calculated using empirical methods.

3.2 Monitoring

A fundamental aspect of tunnel construction in urban areas is the control of subsidence induced by excavation, which is directly proportional to volume loss values. The subsidence that occurs at the surface is, in fact, due to the deformation behaviour 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, 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 pressure at the face and careful construction by means of controlling the grouting pressures and volume of grout mix injected behind the segments are of primary importance in limiting volume loss. Correctly controlled tunnelling thus enables the volume loss during excavation, and hence the predicted subsidence on the surface, to be controlled. Surface monitoring is primarily concerned with the buildings and their foundations, works of art and their foundations, the land on which these works are situated, and their variations in terms of geotechnical and hydrogeological characteristics.

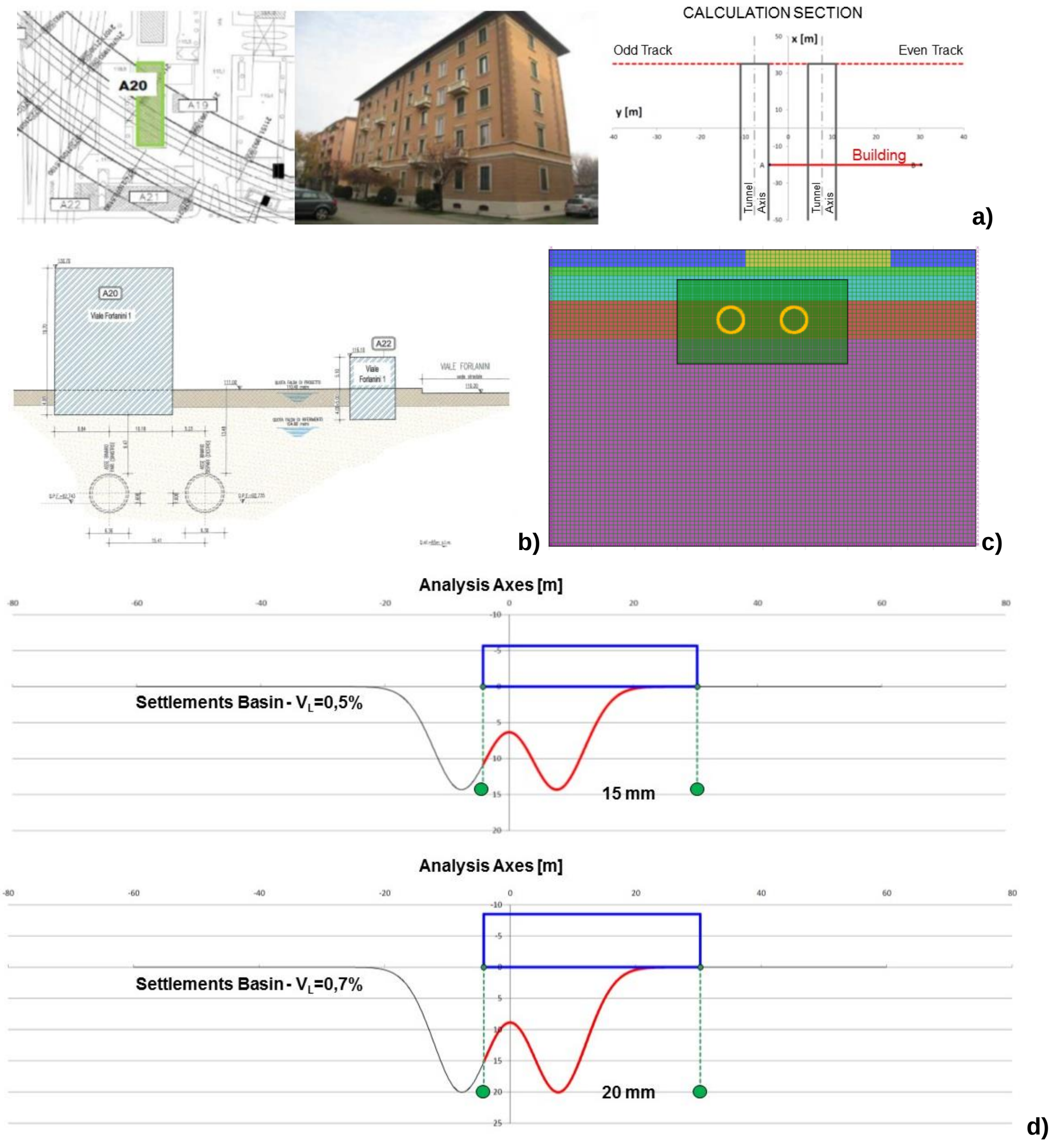


Figure 6. Building A20: a) layout; b) transversal section; c) FLAC model; subsidence basin VL=0.50%and VL=0.70%

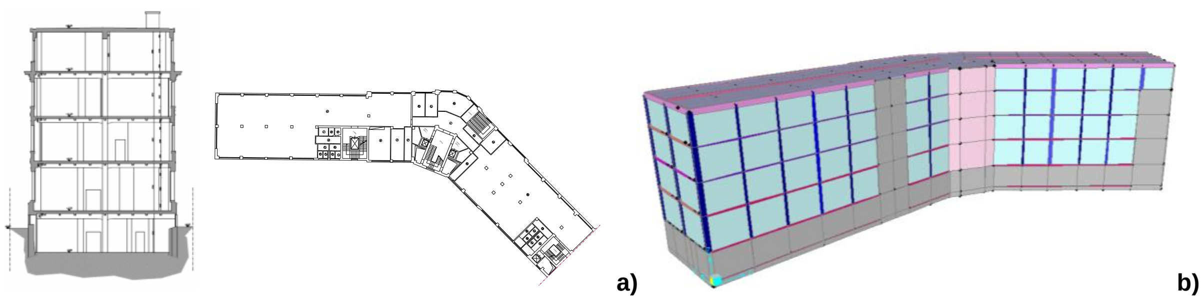


Figure 7. Example of building 3D analysis: a) geometrical characteristics; b) SAP Model

3.3 Back Analysis

The subsidence analysis is intended to provide a prediction of subsidence values, which will be determined by threshold values. In particular, "warning" (20 mm settlement) and "alarm" (30 mm settlement) thresholds are identified.

The building A20 is a five-storey residential building characterized by a direct interference with the even track and partial interference with the odd track. The expected settlements were highest for the excavation of even track, as reported in table 1, but during excavation stage maximum recorded settlements were around 15 mm (Figure 8.a-b), which is a minor value than the one defined as an alert threshold (20 mm).

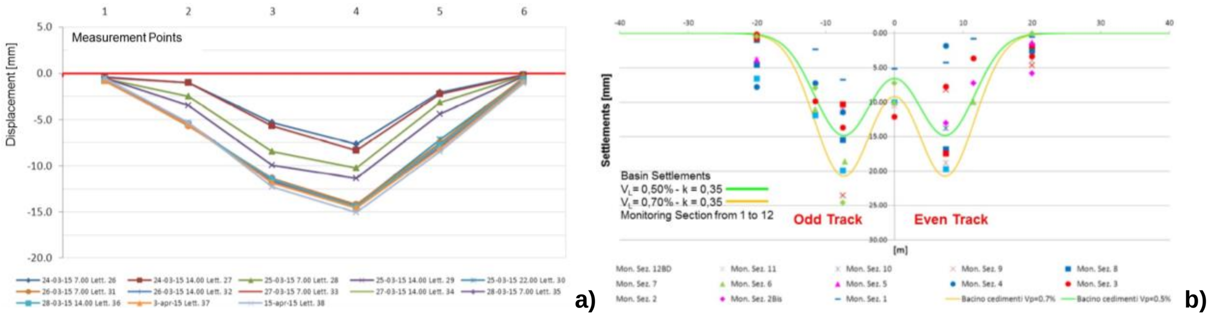


Figure 8. a) A20 measurement point settlements b) Settlements Back Analysis - Section from 1 to 12 (A20 within section 3)

4 TBM parameters

The main parameters defined in the design and "controlled" during construction were those relating to the stabilisation pressure 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 analysis continuously, which made it possible to check the design machine parameters in real time and take appropriate corrective action promptly in order to conform to safety requirements. The excavation-chamber pressure has been defined during the design stage. The FDM analyses have been used to define the pressure at the face and at tunnel countour able to maintain the loss volume in the design limit; this pressure generally is between the condition of active pressure and at rest pressure. Two different kind of data analysis were performed during the excavation of each tunnel stretch, The first analysis concerned the TBM's data process, and consisted in the registration of all TBM's parameters and in their consequent summarization. The second analysis concerned the TBM's data calculate, and consisted in the registration of minimum, average and maximum values of all TBM's parameters for each entire ring advance and in their consequent summarization. Both the data above described have been summarized for each push and compared to the design value in term of: earth pressure, grouting volume, grouting pressure, volume of excavated material.

Furthermore, to have a proper control of the thrust, other parameters have been checked: speed and torque, force main thrust, advance speed. The Figure 9.a summarized, the face support pressure values recorded by the sensors of the TBM's cutterhead, during tracks tunnel excavation. The TBM top sensors recorded pressure showed that the design value was consistently complying with the design value. Also the volume of the excavated material and the grouting volume were continuously recorded, in order to check the balance between the tunnel volume, the volume of excavated material and the grouting volume. The volume of the excavated material was controlled through the weighting of the muck extracted during the excavation. Figure 9.b shows the values defined at the design stage (red area) and the one collected during excavation (blue line): no relevant inconsistencies have been recorded during the excavation.

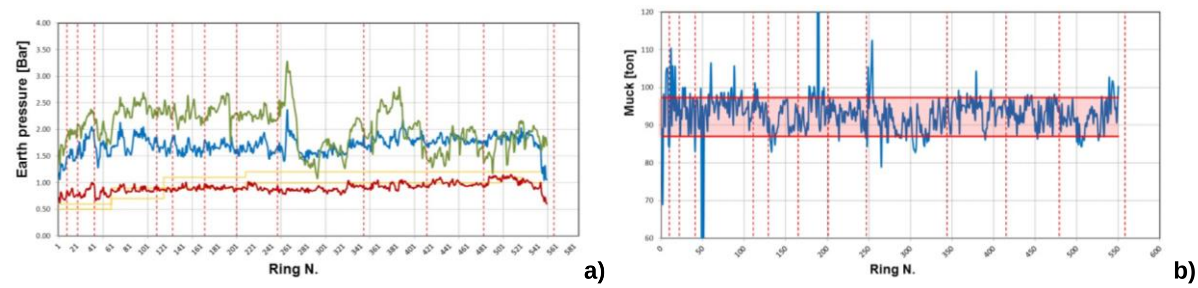


Figure 9. Even track: a) earth pressure; b) muck data

5 Line M4 production

Nowadays have been excavated the Expo section, which link Milan Linate airport to the Forlanini railway station. The second section, which will connect the Linate airport to Tricolore Station is actually in progress. The first section completion lead to make some consideration. Each truck required the installation of 2370 rings. The average daily production value is 15-16 rings/day (considering also work stoppage), Figure 10.a. The maximum production data has been reached during the excavation of the even track with a value equal to 28 rings/day, Figure 10.b. In the period between February and March 2015 the average daily production increased up to 22 rings/day. The production increase is due to the completion of learning curve.

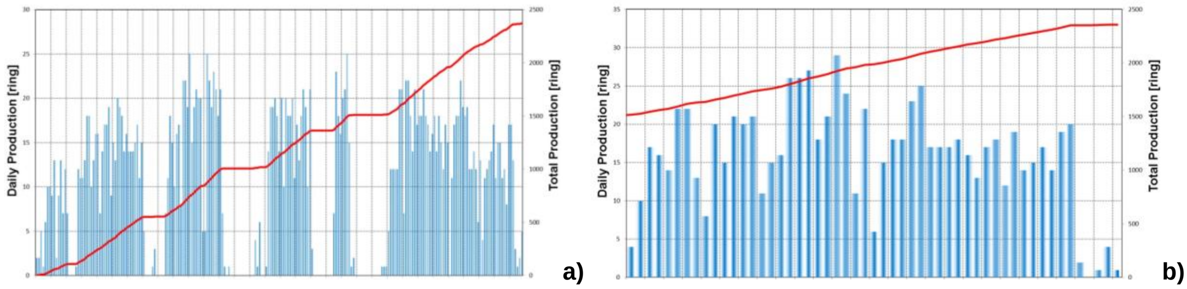


Figure 10. Section 1 Production: a) Odd Track total data b) Even Track maximum values

6 Conclusioni

The new metro line will cross Milan with a length of 15 km from west to east, passing in the south part of the old town. The new line M4 will pass through neighbourhoods with high population densities, so the construction methods have been planned to minimize impact at the surface, to adapt to the underground infrastructure and considering the loosing ground.

The design required an extensive analysis to evaluate the interference with the existing buildings. The paper reported one case (interference A20) as an example usefull to explain the complete applied process from the design stage to construction stage. The success of the operation is borne out by the results of the monitoring performed during construction, which showed volumes of ground lost in line with or below those predicted by the design. The maximum subsidence recorded was always less than that predicted. The results of calculations and checks developed during the design stage have been confirmed during the excavation of the two tunnels of the Expo section. The real time analysis of the TBM parameters and the technical assistance on site guaranteed high production level. The excavation of line M4 is currently in progress with the section 2. The TBM's excavation of section 1, has been performed in safety conditions, without technical problems and respecting the production level estimated at the design stage.

7 References

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