1. INTRODUCTION
The new line 5 of the Milan metro will be an automatic line, with no train drivers. It will serve districts of the city which currently have no underground transport and large volumes of traffic.

Figure 1 illustrates the complete project for the line. The first stage consists of the construction of the section between the Bignami and Garibaldi stations, fully within the borders of the city of Milan. The pages that follow describe the design features of the part of the line, driven using mechanised and conventional methods, lying between the Bignami station and the Lagosta shaft, located between the Zara and Isola stations.

A case history is presented giving details of the delicate passage beneath a pair of major railway bridges, while in service, located in the section between the Ca’ Granda and Istria stations.
2. GEOTECHNICAL CONDITIONS

The context in which the work will take place consists basically of sands and gravels in the presence of the water table. The geomechanical characteristics reported in the table below were assumed for the numerical analysis.

| γ'  | γ  | c' | φ' | K_A | K_P | E   | ν   |
| [kN/m^3] | [kN/m^3] | [kPa] | []  | [-] | [-]  | [MPa] | 0.3 |
| 18 | 12 | 0 | 35 | 0.27 | 3.70 | E_o = 1000 P_a (σ_3/P_a)^0.5 | 0.3 |

where

- γ = natural soil weight
- γ' = effective soil weight
- c' = cohesion
- φ' = internal friction angle
- K_A = active earth thrust coefficient
- K_P = passive earth thrust coefficient
- E = modulus of elasticity or Young modulus
- ν = Poisson’s ratio
- P_a = atmospheric pressure in MPa
- σ_3 = horizontal stress in MPa

The characterisation of the materials in the zone is fairly well known because the city of Milan already has three metropolitan railway lines, an urban link railway line and a large variety of underground structures for different uses. The underground context is also fairly homogenous.

3. THE DESIGN

3.1 The shield driven tunnels

The first section of tunnel to be driven was the mechanised section. It lies between the Bignami and Marche stations passing through four stations already excavated. The EPB (Earth Pressured Balanced) TBM started once the construction site was ready. Fitted with an extremely efficient belt spoil removal system, it achieved average advance rates of around 20 m per day, placing a lining consisting of rings of six concrete segments, plus a key. The lining was 0.40 m thick and the outer diameter of the tunnel was 9.10 m. The average overburden of the section excavated was around 12.0 m and the average pressures applied in the pressure chamber were between 1.2 and 2.2 bar.

Tunnel water proofing is guaranteed by a seal around the perimeter of each concrete segment. Segments and rings are also connected together by steel bolts. Mortar is injected under pressure behind the lining from the tail of the TBM, to fill the ring of hollow space between the extrados of the segments and the profile of the excavation. This prevents undesirable and harmful convergence from occurring, because it minimises the magnitude of “volume loss” during excavation.
3.2 The underground tunnels

Excavation between Marche station and Lagosta shaft was performed using conventional methods, commonly used in the Milan area placing a preliminary lining composed of steel ribs and shotcrete. On the basis of the geology, consisting of sands and gravels with water, ground improvement with concrete injections or jet-grouting columns was employed. This ground improvement was performed at the face and around the cavity working from the surface or, where impossible due to the presence of major cross-roads, buildings or obstructions, inside the tunnel. In the latter case the tunnel sections had a classical truncated cone shape. The tunnels in question have two cross section designs, one for the passage of one train and another or the passage of both trains.

3.3 The stations

The stations located along the first section of the route of Line 5 were as follows: Bignami, Ponale, Bicocca, Ca’ Granda, Istria, Marche, Zara, Isola and Garibaldi. Those through which the TBM passed were Ponale, Bicocca, Ca’ Granda, Istria and Marche, consisting of a central body excavated between rc diaphragm walls supported temporarily by active strand anchors. The depth of the excavation was around
22.0 m from ground level on average (Fig. 6). The exits from this body leading up to the street are closer to the surface, and since, amongst other things, they were constructed at a later stage, they were excavated between provisional micro-piles or steel sheet pilings.

The passage through the excavated stations was performed after first constructing the rc base slab of appropriate size and shape (see figures 7 and 8). The areas around the entrance and exit were strengthened by creating buffers of improved ground. This decision made it possible not to reinforce the diaphragms where the TBM passed through and it made the operations for the arrival and departure of the machine easier (Fig. 9).

Once the TBM had passed through a station, work began on the internal structures consisting of walls and columns in rc cast in situ and of prefabricated horizontal structures, the latter consisting of REP® beams and predalle slabs. In view of these decisions, the design of the various stations was made as modular as possible in order to optimise construction operations and use of prefabricated structures (Fig. 10).
The same technologies were employed for the other stations, Bignami, Zara, Isola and Garibaldi, but the design decisions were made without considering the presence and passage of a TBM.

4. THE PASSAGE BENEATH THE RAILWAY BRIDGES

The railway bridges in question form part of a railway ring line around Milan and numerous passenger and goods trains pass over them each day. The structures were built in the 1920s and consist of six spans resting on two end piers and five columns on direct foundations, constructed entirely in reinforced concrete. The spans have a maximum length of 11 m and the height of the intrados is on average 4.5 m from street level.

The route of TBM passes beneath the central column of the two bridges.

The passage of trains was not interrupted during the works because of the importance of the rail connection.

Since the passage beneath the railway bridges took place in the fourth section of the route, between Ca’ Granda and Istrìa stations, a fair quantity of data was available on the works and on the effects on the
surface from the tunnel already driven. This allowed adequate preparation for the passage to be performed.

4.1 The design steps
The design was performed in various stages. After an initial stage of seeking data that describes the existing structures, a series of on site inspections and measurements were performed. Back analysis calculations were then performed, on the basis of the information acquired and the monitoring data from the tunnel already driven, to estimate the impact of the tunnelling on the bridges. It was decided to realize preventative ground improvement of the zones affected by the passage of the tunnel on the basis of the results of these calculations and a risk analysis.

The guarantees provided by the control of deformation obtained with the EPB TBM and with the mortar injections behind the rings of concrete segments were not considered sufficient by themselves to proceed in the absence of extra protection.

![Figure 13 – Schematic section of the passage](Image)

![Figure 14 - FEM calculation model](Image)

![Figure 15 – Calculation results with and without ground improvement](Image)

4.2 The monitoring plan
A monitoring plan was designed for the passage of the TBM appropriate to the safety requirements for the tunnelling operations and above all to those for the normal passage of railway traffic. The limits set for the tracks, in terms of subsidence and skew, were in fact more severe because it was considered critical for the bridge structures.
Wall inclinometers and a series of levels were used with automatic readings taken every 30 minutes. The observations started when the TBM was at a distance of 20 m from the foundations and they continued until the machine had passed completely under the second bridge. The monitoring was maintained for a further two months in order to detect possible second stage subsidence. It was also performed during ground improvement operations, which are delicate because they involved pressure injections of cement mixes.

4.3 Threshold values
In addition to the monitoring plan, levels to set the thresholds for triggering determined actions was particularly delicate. The maximum vertical movement of the central column of the viaducts was assumed as a “danger indicator”.

Two conditions of pre-alarm and intervention were defined on the basis of the passage of trains, the characteristics of the bridge structures, the expected deformation and data acquired during the excavation of previous sections of the tunnel.

Reaching the first condition triggered an increase in the frequency of monitoring readings and the second condition the shutdown of operations and action to make the TBM safe.

The table below gives the threshold values adopted.

<table>
<thead>
<tr>
<th>Vertical movement</th>
<th>Pre-alarm</th>
<th>Intervention</th>
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<tbody>
<tr>
<td>1.00 cm</td>
<td>2.00 cm</td>
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4.4 The ground improvement decision
Although mechanised excavation provides good guarantees in terms of controlling deformation, in this case it was considered advisable to perform injections of concrete mixes to safeguard the infrastructures and the railway traffic.

The studies showed that hypothetical unprotected tunnel advance would have required the application of high pressures, higher, although by just a little, than the highest ever employed before in tunnel excavation. A field test was also carried out confirming that tunnel advance at high pressures would have had the effect of slowing production and increasing the risk of damage or a machine halt, events to be avoided given the situation.

4.5 Monitoring results
Monitoring activity confirmed the low impact of the tunnelling on infrastructures. The ground improvement provided important confinement action which significantly reduced the “volume lost” and, as a direct consequence, the magnitude of the surface movements.

The chart in figure 16 shows the monitoring results for vertical movement ($y_d$) as a function of the passage of the machine beneath the bridge. It is compared with the theoretical predictions. The maximum subsidence recorded beneath the central column was approximately 3 mm and the subsidence for the side columns was around 1 mm.

The development of subsidence was an immediate reaction to the passage of the face as was predictable from the rheology of the geotechnical formations present in situ consisting of sands and gravels under the water table.
5. CONCLUSIONS
This small contribution gives an idea on the works of the new line 5 of the Milan metro. The design has included line tunnels, stations, shafts, ground improving, etc. As always in urban context, some more aspects, relating to settlement control and on site activity, have been treated. Between these last the passage of the TBM beneath two railway bridges has been chosen for a description. As a precious case history it shows how the solution was discussed, chosen, examined and checked in real-time by monitoring system during the works.

6. REFERENCES