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Brescia Driverless Metro Line – San Faustino Station: A joint work example between client, superintendence, designer and P&CM during the construction phase

A. Merlini
Brescia Infrastrutture, Brescia, Italy

A. Breda
Superintendence Archaelogy Fine Arts and Landscape for the Provinces of Bergamo and Brescia, Medieval Archaeology Official, Brescia, Italy

I. Carbone
Consultant and past P&CM Manager for Brescia Driverless Metro Line, Milan, Italy

M. Gatti
Rocksoil S.p.A., Milan, Italy

ABSTRACT: The archaeological investigation, requested by the "Brescia Superintendence" during the construction phase of the Brescia Driverless Metro Line, highlighted significant archaeological evidences at the areas of the San Faustino Station. The archaeological findings describe part of the historical access system of the city and the nineteenth-century bridge with a double arch that allowed crossing the protection moat of the Venetian Walls (thirteenth century). The Brescia Superintendence required to revise the approved project of the Station, given by the value of the archaeological evidences and make them visible to the station passengers in trans-it. The station, located at a depth of about 30 m below the surface level, has been opened in 2013. The paper highlights the importance to have a sensitive Client who drives all the stakeholders, specially the Designer and the P&CM, developing innovative solutions, in terms of architectural approach and construction technologies.

1 INTRODUCTION

During the 1980s, road congestion in the vicinity of Brescia rose dramatically, resulting in the City Council becoming interested in the adoption of a new mass transit platform to provide an alterative means of access around the city. Following studies of several mass transit systems, it was decided that the development of a light metro would be the most suitable option.

In 1989 Brescia City Council commissioned ASM Spa with the drafting of the tender. At a later stage, in 2003, Brescia Mobilità Spa awarded the construction work, via a Design and Build Procurement procedure, to Ati Metrobus, a joint-venture composed of Ansaldo Sts, Ansaldo Breda Spa and Astaldi Spa, which executed the works up to 2011. Brescia Infrastrutture S.r.l., a company fully owned by Comune di Brescia, was set up that year. The company brought the project to completion, tested it and started operation of the entire line in March 2013.

The Brescia Metro is a rapid transit network serving Brescia, Lombardy, Italy. Today, the network comprises a single line, having a length of 13.7 km and a total of 17 stations from Prealpino to Sant´Eufemia-Buffalora, located respectively at the north and southeast of Brescia (Figure 1).

All stations have been outfitted with automated doors along their platform edges. This is to act as a safeguard against passengers entering onto the track, accidentally or otherwise, while

also increasing passenger comfort by reducing their exposure to wind and noise from train movements through the stations.

2 BRESCIA DRIVERLESS METRO PROJECT AND SAN FAUSTINO STATION

2.1 *Metro line*

Brescia's Automatic Light Metro was built in a heavily populated area and it stretches for about 13,7 km of double-track line divided as follows (Figure 1):

- approx. 3 km of double-track excavated using the Cut & Cover method;
- approx. 6 km of double-track bored tunnel, excavated using the TBM (∅ 9,15 m);
- 5 km of double-track line, including trenched, street-level and elevated sections (1,7 Km);
- 17 stations, of which 13 underground and 7 above surface;
- 13 underground shafts for safety access;
- 1 depot-workshop running along 5 km of track.

A first archaeological survey was conducted by contractor Ati Metrobus during the tender stage. The survey was based on historical documents that highlighted the existence of archaeological remains in the city fabric, particularly in the oldest part of the city centre. No preventive survey involving excavation and aiming to show what exactly was lying underground was conducted. Once the contract was awarded to Ati Metrobus, the archaeological activities got underway as follows:

- a risk assessment report relevant to the intended works was conducted prior to the opening of the sites;
- the Archaeological Heritage Office supervised and offered assistance to the earthmoving works from the time of the opening of the sites (starting in April 2006).

Brescia Infrastrutture S.r.l. worked in close collaboration with the Archaeological Heritage Office; this collaboration allowed to fully understand the importance of surveying and hands-on knowledge, of classifying individual findings within the historical and archaeological context, of properly assessing the repeatability or the uniqueness, as the case may be, of a given find so that it can be fully appreciated by users.

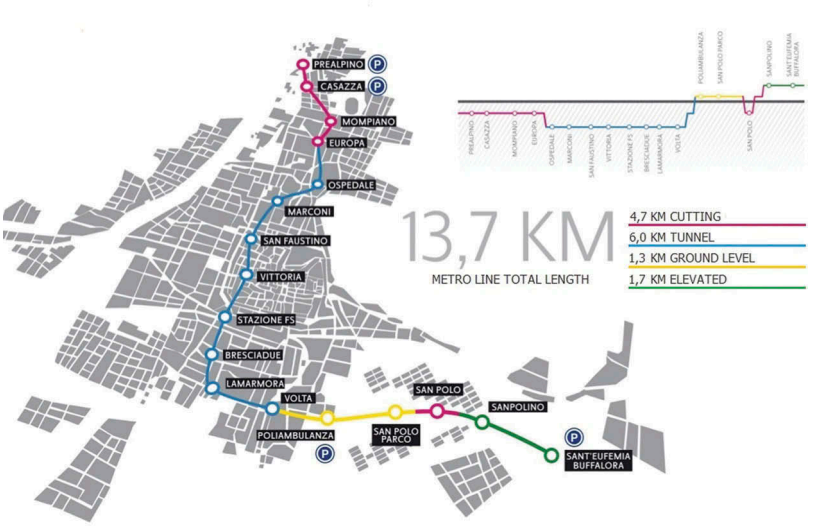

Figure 1. Brescia Metro Line Layout.

2.2 *Archaeological activities related to the construction of San Faustino Station*

One of the main urban areas where has been planned an excavation with archaeological evidence is the one of San Faustino Station (Figure 2). The surveys conducted at the various stages have unearthed: *a)* the Venetian walls (the old city walls) similar in shape and structure to those visible in other points of the city – Porta Pile or Porta Sancti Faustini (1254) with its flooring (Figure 3.a), the gateway to the city from the north (including a nineteenth-century bridge which in 1818 replaced the drawbridge, see Figure 3.b, crossing the moat and composed of two almost intact arches); *b)* a section of the Visconti walls basement (datable to the second half of the fourteenth century) which was superimposed by *c)* the next curtain belonging to the Venetian era (early sixteenth century; today well preserved in elevation for almost 300 meters along the adjacent Fossa Bagni, corresponding to northern moat of the city walls, d) the double archivolt and bridge-channel system (1518–1522) through which the Garza torrent, coming from the north, first passed under the counterscarp bank of the moat, then crossed the moat and finally entered the city crossing the walls and the embankment behind it, e) the remains of various medieval and modern structures located within the urban belt downstream of the gate.

The figures 4 and 5 show the relationship between the surface area of the station (in red), and the excavation work and archaeological remains actually found (in green) or theoretically existing (in blue). The assessment of the relevance and significance of the findings from an archaeological point of view determined the modification of the station project design.

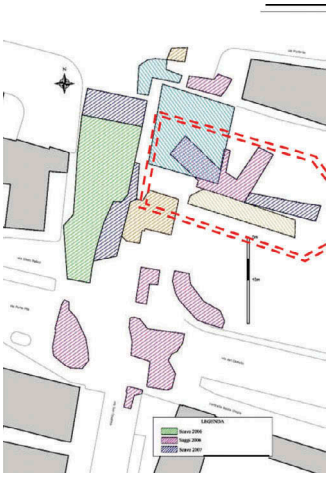

Figure 2. San Faustino Station: dashed red line identifies Station layout.

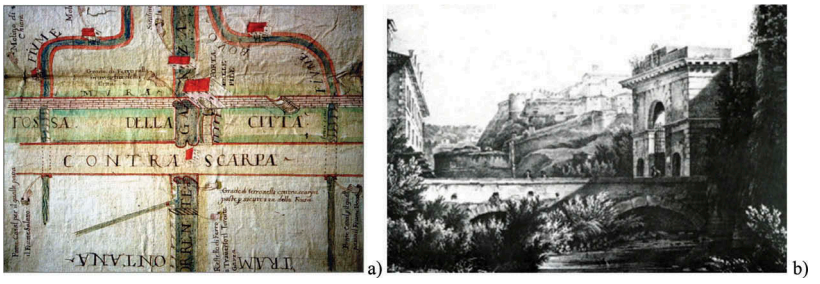

Figure 3. Porta Pile: a) Iseppo Cuman Map (1667, Brescia, Archivio di Stato, ASC 999); b) Stone bridge, built in 1818, found during metro line construction work (engraving of Fausto Pernici (1840–1850).

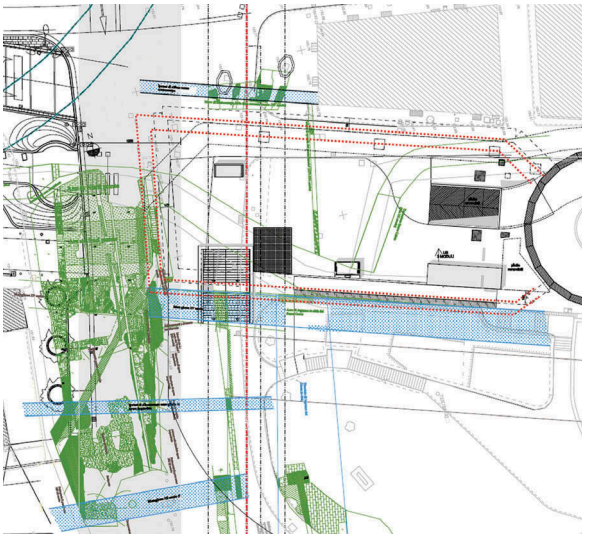

Figure 4. San Faustino Station (red dashed line), archaeological findings (green areas), historical structures at the ground level (light blue areas).

Figure 5. Archaeological excavation of the medieval gate and the stone bridge.

Further surveying was conducted in support of the excavation work until the completion of the project, as follows:

- in March-April 2009 excavation for the construction of the station took place in the moat alongside the Venetian walls;
- from November 2011 to September 2012 excavations took place to facilitate the rearrangement of the underground utilities layout and to build the access to the station;
- at the start of 2013 took place the final arrangement on the south side of the station.

3 SAN FAUSTINO AND THE ARCHAEOLOGICAL FINDINGS: AN INNOVATIVE APPROACH OF THE ARCHAEOLOGICAL PROJECT

The archaeological survey (Gallina, 2003) has been carried out along the entire route of the new metro line (13 km), in addition to the various and complex actions related to the urban impact assessment (at that time prescribed by D.P.R. 554/1999 on the organization of public

works, which was equivalent to the current D.L. 50/2016 – Code of Public Contracts). The study has been commissioned by ATI to a professional archaeologist, qualified to the task and above all well aware of the history of the city constantly assisted by the Superintendence for Archaeological Heritage of Lombardy. The investigation has been based on two types of sources:

a) historiographic sources (published and unpublished written documents, iconographic documents);
b) the dense archaeological literature that dates back to the seventeenth century for Brescia and that since the fifties of the last century has grown exponentially, as a result of numerous emergency excavations and research that have accompanied the impetuous transformations of the contemporary city.

Obviously, the greatest attention has been paid to the urban districts of via Verdi, via Dante Piazzale Battisti, via San Faustino, where the excavation of the "Vittoria" and "San Faustino" stations has been designed, the two areas of the historic centre that would affect by the archaeological findings. The survey underlined a lot of critical issues for both areas, in particular, the certain presence of the archaeological findings related to the main gate of the city and the adjacent walls of the Renaissance has been highlighted for the San Faustino Station Area. In addition has been detected also the possibility of unearthing of some structures belonging to the fortified apparatus of the Middle Ages. The prevision is confirmed by the findings made during the various phases of the archaeological investigations carried out between 2006 and 2007, but extended with necessary assistance until the year 2012 (Figure 2 – Figure 4).

Brescia Infrastrutture and the agreed on the advisability of an *alternative project* in consequence of the high density of archaeological findings distributed in relatively small area (3000 sq). The new project should allows the construction of the station (not located nearby due to urban constraints and logistical opportunities) and, at the same time, the preservation of important evidence of the city's history.

A solution has been defined with the Institutions involvement (Archaeological Superintendence of Brescia, Cremona e Mantova; Superintendence for Archaeological Heritage of Lombardy; Directorate General Archaeology – Ministry for Cultural Heritage and Activities). At the end the station has been built in the predestined place, while ensuring the conservation of most of the ancient structures and the visibility of significant portions of the same within the station.

The station's structure originally should have been built through open cut excavation by building the station retaining walls first, followed by excavation and the total removal of soil and material in the designated area; this would allow free access to the TBM, as was the case with the other deep-level stations involving the excavation of a natural underground tunnel.

Given the importance of the archaeological layer along the north-south axis of Cesare Battisti Plaza and given the possibility to carry out a single open cut excavation in the area occupied by the Fossa Bagni old moat between the axis of the metro line and the existing underground car park, the station project was reviewed with substantial modifications to both the spatial distribution and the construction technique.

The entire distribution of the vertical connections was included in the openly excavated volume, while the platforms, maintained in their original position, were built by widening the underground tunnel (excavated with the TBM boring right through), allowing us to safeguard the archaeological layer above. The archaeological remains found in Cesare Battisti Plaza caused inevitable delays in the works, which in turn led to a series of variations in the San Faustino Station design, conceived to respond in the best possible way to the complications encountered. The revision of the station architectural design, was aimed to answer to the following specific requirements:

– first of all, to minimise the impact of the works on the archaeological findings;
– secondly, to follow the same principles that inspired the design of the other deep-level stations: namely, that the station should be perceived as a single volume without intermediate horizontal levels and that natural light should reach the platforms.

The Heritage Office requested that the archaeological findings be exploited and that solutions to allow the findings deemed most interesting to be in view within the station, compatibly with the station layout, be thought out. These findings include some sections of the Venetian walls and the counterscarp, as well as the system across the Garza stream and the arches of the nineteenth-century bridge. The station is embedded exactly along the width of the moat, which means that the longer sides of the station volume run along the Venetian walls and the counterscarp. The design principle with respect to the archaeological findings was therefore to make the Venetian walls, the moat and the counterscarp available for the public to view. This solution allows the public to admire sections of the ancient walls on the south side, a part of the bridge at the foot of the main stair access on the west side and the round arches at the point where the Garza stream crossed the counterscarp to reach a rectangular weir cut into the width of the moat (see Figure 6.a).

The Venetian walls, sectioned in that stretch by the ramps, have been left in full view in the cladding of the wall masonry that runs along the stairs leading to the upper concourse (south side). The cross section has been left visible to the side of the stairs (see Figure 6.b).

In addition, a long and particularly well-preserved section of the Venetian walls has been left visible along the south side. It can be admired from inside the station through an ad hoc 15-metre long glazed opening. The section made in the vicinity of the Venetian walls and the construction of the all-glass lift shaft let light into the station, while allowing us to respond to the design requirements of a single volume and natural light on the platforms. Due to the severe constraints imposed by the context and the restricted space available, it was only possible to meet the said requirements as far as the lower concourse level (Figure 7.a). A view of the bridge, whose depth has been left partly uncovered so that the structure can be appreciated, opens along the west side of the upper concourse. A photograph, on display beyond the perimeter wall masonry, offers a better understanding of the whole system (Figure 7.b).

Furthermore, a part of the front section of the counterscarp is visible from inside the station through an opening located on the north side of the upper concourse. The large glazed

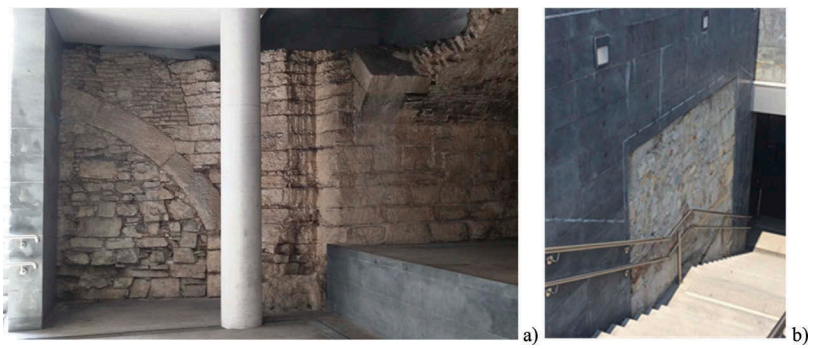

Figure 6. a) Round arch of Garza stream; b) Venetian walls section visible to the side of the stairs.

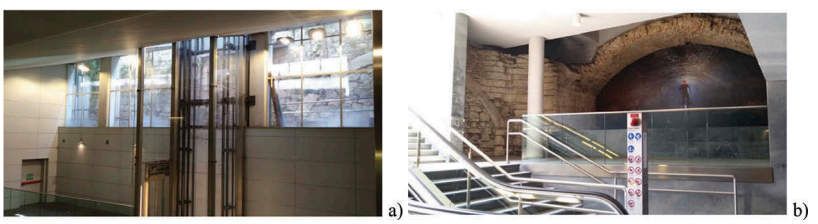

Figure 7. a) Large section of Venetian wall (sixteenth-century) visible along the south side of the station; b) nineteenth-century stone's bridge, upper atrium view.

Figure 8. La grande finestrature che consentono al pubblico di percepire lo spazio della larga fossa che circondava le mura urbane: a) a sud verso le mura b) a nord verso la controscarpa.

opening on the south side (Figure 8.a) over the Venetian walls and the opening on the north side (Figure 8.b) over the counterscarp allow users to conjure up a mental picture of what the ancient system was like, giving them a sense of measure of the space that constituted the ancient moat.

4 THE CONTRIBUTION OF THE P&CM DURING PROJECT DEVELOPMENT

The new Metro Line of the city of Brescia and its metropolitan area marks a historical passage in the city life and determines a new way of relating with the urban fabric, the Contracting Authority decided to use technical engineering services for the Project & Construction Management (P&CM) of the works.

The international tendering procedure has been awarded by a group of engineering companies. with mandated Metropolitana Milanese S.p.A., today MM S.p.A., was the Authorized Representative. The P&CM is a professional service that uses specialized project management techniques to oversee the planning, design, and construction of a project, from its beginning to its end and the first months of operation. In the case of Brescia Metro Line, the P&CM went beyond the mere technical and regulation control by enlarging their operating area to the comprehension of the reasons behind the design, attuning themselves with the choices and prescription of the contracting authority. This Approach was fundamental for San Faustino Station and it is the normal way of work of MM S.p.A., which is the engineering Company of the Milan's Municipality with more than 60 years of experience in Metro Line realisation in Italy and abroad.

The Brescia Metro Line was a complex project, the P&CM decided to apply an organisational model which comply with the Contracting Authority needs and project requirements. The organization of P&CM includes a General Coordinator and a series of specialist and multidisciplinary managers who coordinate specific control work groups (cost, detailed and constructional design, Construction Supervision, safety coordination during the construction phase, for civil works and civil installations, railway installations and automation, rolling stock).

One of the main organisational choices of P&CM, which success has been later proved by results, was to employ most of the group engaged for the control phase of the project also for the Supervision during construction phase. The same choice has been made also for the railway system/automation and rolling stock, relatively to the phase of tests and trials, pre-operation and the first months of operation. The latter aspects are very tricky phase for a public transport system in general and, in particular for a Driverless Metro Line.

Particularly important were the interface and assistance activities to the Testing Committee and the Safety Committee. In particular, the representatives of P&CM worked from the outset within the Safety Committee – composed by representatives of the Transport Ministry and Contracting Authority to follow step by step all the various phases of the design – providing their contribution to the analysis of the documents submitted in progress by the Contractor and to the technical and contractual approval of the P&CM.

5 ENGINEERING: THE DESIGN AND CONSTRUCTION PHASE

The identification of archaeological finds required the modification of the architectural and structural design of the station, using underground excavation construction systems, without impact on the surface level and on the first thickness of the anthropic layer, where there were mainly placed the pre-existing to be preserved and enhanced.

The typological scheme of the stations located along the metro- underground section excavated by the TBMs referred to the cut & cover construction method. The San Faustino Station has been designed for cut&cover method only for a small section, the main longitudinal part of the station, containing the platforms of the station, has been located in a deep tunnel. The bottom-up shaft has been strategically located on the sides of archaeological finds, between the moat of Fossa Bagni and the car parking (Figure 9), by this way has been possible realise some openings on the retaining structures and make visible the archaeological finds. The portion of the shaft located along San Faustino Street has been connected with the deep tunnel. The shaft housed the vertical connections of the station, such as stairwells and elevators, technological and system components; the bottom part of the shaft includes the passageway to the two directions of travel of the trains, while most of the platforms have been placed inside the underground tunnel.

The civil works have been performed in a geotechnical context constituted by a 5,00 m thickness layer of natural and anthropic fill and by heterometric and polygenic gravel in a silty sand matrix, characterised by a non-cohesive behaviour. The geotechnical tests performed identified: a deposit with no cohesion and friction angle equal to 38°, while the Young's modulus (E) varying from 40MPa at the ground level to 220 MPa at the tunnel level. The water table height is 121,00 m above the sea level corresponding to a depth of 25–30m from the ground level and influences only partially the civil work. For the excavation of the station reinforced concrete diaphragm walls (open bottom-up method) executed by the use of hydro-mill were provided; this technology has been selected to guarantee the minimum verticality tolerances requested due to the reduced thickness available for both temporary and permanent structures. The use of the hydro-mill has also ensured better continuity and hydraulic seal of the joints. The diaphragm walls have been characterized by a thickness equal to 1,00 m and a width of 2,80 m, the diaphragm have been casted alternatively (primary and secondary

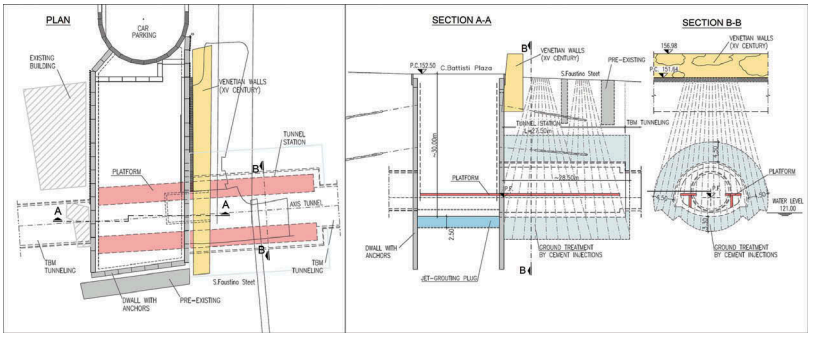

Figure 9. Intervention overview: general plan and representative cross-section.

panel). The maximum excavation depth was 28,00–30,00 m, for this reason the depth of diaphragm walls was 43,00 m (embedded part equal to 12–13 m).

In some sections, the ones close to buildings and in correspondence to the existing car park, the construction of the diaphragms was brought forward by the installation of micropiles to protect the foundations of the buildings. The diaphragms walls affected by the passage of the TBM have been reinforced with fibreglass bars, according to the logic of *soft eye*.

In order to guarantee the seal of the bottom of the excavation with respect to the hydraulic pressure, it was decided to create a bottom plug by means of jet-grouting columns characterized by a nominal diameter of 1400 mm and a mesh of 1,05 m per 0,95 m. The execution of a field test led to calibrate the operating parameters of the treatments, with specific energy of 38–40 MJ/ml. During the excavation phase, the diaphragms have been contrasted by the installation of ground anchors (6–8 steel cable strands), arranged in numerical order of 2 per panel following a lowering excavation step of 5,00–8,00 m.

The design and execution of the station tunnel was a very demanding work. The ground improvement around the tunnel face has been performed by grouting activities carried out from the surface and localised in the areas identified as "free" as a result of the execution of archaeological surveys. The overburden in correspondence of the tunnel crown was about 15–18 m. The soil injection technology with cementitious mixture and integrative water-proofing mixtures by "tube-a-manchette" equipped with 3 valves per metre has been adopted. Since drilling had to be carried out from rather restricted areas, inclined drilling sequences have been defined, with the aim of obtaining 1,60 m by 0,80 m meshes at the bottom of the perforation, thus imagining a penetration radius around 90 cm. The station tunnel had an excavation diameter of 18,00 m, with a total excavation area of 168 m^2; a 4,5 m thickness around the tunnel crown was consolidated and about 3.5 m in correspondence of the invert, considering the modest hydrostatic head.

The construction phases of the works have been also modified with respect to the solution envisaged in the project and adopted for the other stations. The station excavation, originally, has been designed providing the excavation up to the level of the bottom slab, allowing the break-through of the TBM, i.e. through the station completely excavated. The construction of the metro line took place in sections from station to station; inside the excavated station the preparations for TBM starting were built, such as cradle and thrust frames, or slab for TBM arrival at the station after the tunnel excavated section. In the case of the San Faustino station, on the other hand, the TBM was forced to bored through the station, i.e. without having completed the excavation of the station; this was due to the accumulated delays, compared to the excavation schedule of the TBM, with the sets out of the archaeological variant. In order to allow the TBM tunnel to be maintained in safety, the excavation of the station was stopped at the necessary height to guarantee an overburden of 5,00 m in correspondence of the tunnel crown. The numerical analyses shown how this covering could guarantee of static stability conditions for the segmental lining ring; a reduced load on the crown would have decompressed the joints between the precast segments, thus not allowing the monolithic nature of the lining. In order to proceed as quickly as possible with the excavation of the station shaft, so as to start the construction of the civil works and the subsequent installation of the systems, excavations were carried out in the portion furthest from the transit way of the TBM, separating the two areas of the station, located at different levels of excavation, through the construction of a retaining wall by jet-grouting. Once the excavation by TBM had been completed for the entire metro line, it was possible to dismantle the service structure inside the tunnel serving the TBM (power lines, piping for supplies, etc.) in the sector inside the San Faustino station and proceed with the completion of the excavation of the station. For this reason, a set of rings was shoring up with steel arches and plates at the joints, by this way the excavation machineries could operate at the tunnel crown in safe conditions.

It was then possible to open a first window by demolishing some segments of the lining and proceed with the progressive filling of the tunnel, through the excavation resulting soil and its demolition until the excavation reaches the bottom side of the station. Once the excavation of the station between diaphragms was completed, up to the mechanized excavated tunnel, it was possible to proceed with the excavation of the tunnel station, enlarging the excavation already carried out by the passage of the TBM. The excavation proceeded from the station shaft

Figure 10. Work Phases: the excavation of the station shaft and of the tunnel station.

towards the tunnel, thanks to the consolidation already carried out from the surface. The excavation was carried out for single excavation step of 0.90 m, by installing a sprayed concrete layer (30 cm thickness) reinforced by 2 IPN240 steel arch; the precast segmental lining was removed together with the ground of the tunnel front. The delays accumulated with respect to the original time schedule led to the speeding up of the internal structures construction through the use of precast elements; the structural system also had to adapt to the new architectonical layout of the station, providing large spans that could enhance, during the operation of the station, the view of the archaeological finds detected.

6 CONCLUSIONS

The Driverless Metro Line of Brescia and, in particular, San Faustino Station represent the opportunity to create a dialogue between past and present.

The fundamental choice of the Municipality of Brescia and of the Companies which have taken the leadership of the Project over the years, was to involve the Superintendence from the beginning and be supported by specialists (designers, P&CM and contractors) able to provide the maximum contribution to the design and implementation of innovative solutions, considering a global working method, which provides a constant cooperation between the different stakeholders involved in the project: Institution, Client, Contractor and Designer.

The city of Brescia has always been strongly oriented towards innovative solutions. It's enough mentioning the Brescia is one of the few Municipality in the world to have built a driverless metro in a metropolitan area of about 400,000 inhabitants.

The San Faustino Station is able to enhance the archaeological findings maintain its functionality, thanks to a perfect insertion into the pre-existing area; this result was achieved with a fully revised of the technical solution for the station, adapting the project to the findings and applying very demanding construction solution.

REFERENCES

Archivio di Stato Brescia, *ASC 999*

Gallina, D. 2003. *Brescia – Progetto Metrobus: Valutazione di impatto archeologico*, Ati Metrobus, Brescia.

Lunardi, P. 2008. *Design and construction of tunnels: Analysis of Controlled Deformation in Rock and Soils (ADECO-RS)*. Berlin: Springer.

Merlanti, P., Bellocchio, A., Sicilia, R. 2008. Analysis and prediction of subsidence phenomena induced by excavation employing an EPB-S in the works to construct the Brescia metro design predictions and back-analysis, in *Proceeding of AFTES International Congress 2008: "Le souterrain: espace d'avenir"*, 6^{th}-8^{th} October, Monaco, Germany.

Zanirato, L. 2018. *Metropolitana di Brescia – Una nuova concezione di mobilità. Brescia subway – Mobility redefined*, Massetti Rodella Editori, Roccafranca (BS), Italy.