The implementation of an underground infrastructure in a complex archaeological context: some experiences from design and construction of the new Line C of the Rome Metro

Andrea SCIOTTI
Roma Metropolitane S.r.l; Project Manager of Line C
Eliano ROMANI
Metro C S.c.p.a.; Engineering Manager of Line C
Mauro D'ANGELO
Metro C S.c.p.a.; General Manager

The new Line C runs through the historic city center and crosses the area with the highest density of monuments and archaeological elements above and below the ground level. A proper handling of the "archaeological issues" is playing a significant role in the implementation of this new underground infrastructure. The focus of this paper is on some case-histories about design and construction aspects related to the archaeological issues: the method to complete the archaeological investigation simultaneously with the construction activities, the solutions for the construction and the enhancement of archaeological context in San Giovanni Station, the methodological approach adopted for the preservation of the monuments.

Introduction

Line C is the third line of Rome underground; at the end it will cross the city from the southeastern area (Monte Compatri-Pantano) to the northwest (Clodio-Mazzini), for a total length of 25.6 km and 30 stations; it is also the first fully automated underground line of Rome.
The contract was awarded at the end of 2006, between Roma Metropolitane S.r.l. (the Contracting Authority) and the General Contractor Metro C S.c.p.a.
Roma Metropolitane S.r.l. works on behalf of the Municipality of Rome to carry out all the functions associated with the implementation of new Line C (preliminary design, tender procedure, contract awarding, technical and administrative supervision and control, project management).
Metro C ScpA is a Project Company which acts as General Contractor for the Line C. It consists of Astaldi (representative), Vianini Lavori, Ansaldo STS and CMB, which deals with the construction of Line C in all its phases: from the final design to the archaeological surveys, from the construction (tunnels, stations, civil and railway plants, trains) to the monitoring, from the preventive tests to the 'commissioning' and start-up.
The activities started in 2006 with the archaeological surveys and the final design. At now there are 21 stations and 18 km of line in operation. The first stretch, between Monte Compatri-Pantano and Parco di Centocelle (15 stations and 12.5 km of line) was opened to the public in November 2014; the second, from Parco di Centocelle to Lodi (6 stations and 5.5 km of line) was opened in June 2015. Another station, San Giovanni, will be soon in operation. Two more stations (Fori Imperiali and Amba Aradam Station) are under construction in T3 stretch (3 km of line), within the historical center of the city (Fig. 1).

The archaeological metro

The structure of the route within the historic center of Rome and the consequent need to cross vertically the entire archaeological layer to link the underground, (where the tunnels and platforms are located), with the surface (where the accesses are present), have given to the Line C the connotation of "an archaeological underground". This infrastructure is not only a means of transport but also a means of knowledge and a possibility to enhance the historical heritage of the city.
The planning and the beginning of construction of Line C was developed in the same time during which the Italian archaeology underwent a profound transformation. There was a gradual transition from emergency to preventive archaeology (introduced by Law 109/2005), intended as the only adequate scientific "modus operandi" in a so important archaeological context like the center of Rome.
For the Line C, right from the preliminary design stages (1996), the Archeological Authority (Superintendence) of Rome was called for the execution of a huge archaeological investigation and it reiterated the need of a thorough geo-hydrological survey in order to study the interaction between the line and the monuments before expressing any final opinion. Between 1998 and 2003, during the development of the preliminary design phase and the definition of the financial terms (completed in 2004), an extensive archaeological investigation was carried out.

From May 2006, following the tender awarding to a General Contractor, that is responsible for the definitive/executive design and construction of Line C, Metro C ScpA began an important archaeological investigation with restricted excavations in 28 different sites in order to obtain useful data to develop the final design of some Line C stretches.
The Superintendence assumed the scientific supervision of these archaeological investigations to safeguard the archaeological heritage.
In the central section, the archaeological investigation phase was very very complex because Metro C and Roma Metropolitane had to arrange a lot of clarifications and methodological refinements with the Superintendence and other competent authorities during the excavations. First of all, it was acknowledged that the investigation areas defined in the first phase were not sufficient to reconstruct the existing underground archaeological structures. Thus, the investigation areas increased in width and depth with the implementation of excavation supports which had a local destructive character for buried artefacts.
As reported in the document "Cantieristica archeologica e opera pubbliche la linea C della metropolitana di Roma: tratta T4 stazioni San Giovanni, Lodi. Indagini 2010-2011", (R. Rea; edited by Electa, Milano 2011) the experience of Line C showed that the presence of a dense network of underground services, the hydrogeological characteristics of the subsoil and the complexity and density of the stratified urban fabric influenced the investigation of very deep archaeological layers in the central areas and in the outskirts of Rome, where the Line C stations and shafts are going to be constructed. The need to remove the remains found and the presence of ground water were problems not easy to solve. Thus, the preventive archaeological excavations stopped before reaching the "geological" layer (without archaeological interest) and a review of the approved preliminary investigation planning was necessary in order to define a different approach to end the archaeological activities.
It was necessary to create, in advance, relevant containment works, supports, and protections of the excavations in order to carry out a real extensive archaeological investigation and to reach the depth of sensitive layers (about 15-20 meters from the current ground level) near pre-existing buildings, roads, monuments, etc. In many areas, the protections of the excavations did not correspond with definitive ones and the creation of "losing" preventive structural works resulted uneconomic or not even feasible.

Fig. 1 – A view of the construction site of Fori Imperiali Station (central stretch).

The Scientific Committee of the National Archaeological Authority, having analyzed the situation, ratified that is useful authorizing the execution of the containment works necessary to end the archaeological excavations, where required and even if they cross the remains. Therefore, the Committee emphasized the impracticality of ground consolidation from the surface level that are typically used in all excavation areas to waterproof the soil without preventive archeological survey - such as jet grouting, injections, etc. - because these consolidation activities are potentially destructive of the archaeological layers. Instead, the Committee affirmed that is necessary the execution of all structures along the perimeter of the excavations of the stations and shafts - such as diaphragms, piles and micro piles - to complete the archeological investigations ensuring the safety of people and the preservation of surrounding buildings. In summary, the Committee ratified that the continuation of the preventive archaeological surveys had to proceed simultaneously to the construction activity of Line C underground stations and shafts.
Thus, as regulated by current legislation, the preventive archaeological survey is divided in two phases. The first one is used to verify the presence and consistency of the archaeological deposit in the subject areas in the planning; while the second one starts at the end of the final and executive design of the underground works and it is intended to clarify the nature and complexity of the archaeological deposit. At the end of the second phase, which includes the results of excavations and archaeological surveys in a wider area, the compatibility of the public works with the protection of the archaeological heritage will be concretely evaluated.
Therefore, in contrast with these forecasts, the outcome of the activities carried out jointly with the Superintendence at the stage of preliminary design resulted, in the case of Line C, that archaeological protection requirements should also provide for a phase of activities to be performed during the construction works (Fig. 2).
Such activities are detailed and regulated by the Archaeological Hand-book, drawn with the Superintendence in the final or executive designing phase, following all the executable preliminary investigations. The scope of the Handbook is to define the archaeological activities to be carry out simultaneously with the construction of underground works.
On the basis of the results of the first archaeological surveys and of the extent and the quality of the archaeological deposit to be explored, it is possible to establish the

Fig. 2 – Archaeological excavation during the construction of the station (top-down method).

methods and resources used to complete the excavation and to ensure the protection of the archaeological findings.
For each archaeological layers is determined the excavation mode, the type and the quantity of structures to be investigated and removed, the average daily productivity based on previous experiences. These data are necessary to estimate the real construction time and to evaluate reliably costs of the public works.
The Archaeological Handbook is used for the first time during the construction of the Line C San Giovanni station (2010).

The constructive solutions: the case of San Giovanni station

One work of many that required adopting construction techniques suitable for responding to the problems present of a geological/geotechnical, archaeological, and territorial nature, with a high density of buildings and underground utilities, is certainly the San Giovanni station, an interchange between Line C and existing Line A, in T4 stretch.
The station is inserted in the difficult urban setting of the Appio - Latino neighbourhood (Fig. 3): it extends along Via La Spezia next to the existing San Giovanni station of the Rome Underground's Line A.
The station structure is rectangular, 140 m in length and 22 m wide, and it reaches a depth of 35 m below ground level. It consists of 7 horizontal structures, and shares a border with the existing Line A station to allow for passenger interchange; the geometrical characteristics of the main structural elements are summarized as follows: Perimeter diaphragm walls 280 x 120 cm and 56 m in length; Roof slab (120cm thick) at 36.68 m ASL; Intermediate slabs (100 cm thick) at 31.50 m ASL, 26.50 m ASL, 22.00 m ASL, 15.50 m ASL; Platform slab (30 cm thick) at 10.50 m ASL; Foundation slab (150 cm thick) 8.29 m ASL.
The encountered geological/geotechnical units (Fig. 4) are a transition from the volcanic units of the eastern periphery of the city towards the fluvial or marine units of the historic centre of Rome (the Tiber's ancient riverbed).
Starting from ground level, the first stratum consists of made ground [R], with thickness reaching 13 – 16 metres. It is a heterogeneous material with sandy-silty matrix mainly of pyroclastic nature. These materials offer fair shear resistance in effective tensions accompanied by modest cohesion.
This is followed by a stratum of recent alluvial deposits [LSO] that have filled deep cuts with often variable thicknesses, reaching the level of about 17 metres at San Giovanni station. In terms of granulometry, it consists mainly of silty sands and clayey silt, blackish in colour, from low to medium stiff.
The succession of the units composing the Pleistocene deposits is represented, proceeding from top to bottom, by an initial unit [ST] consisting of an alternation of white or yellow silty sand and clayey sandy silt [STa], with carbonate concretions and localised levels on travertine concretions, with a high degree of thickening and of medium to high dense, followed by a unit consisting of clayey silt and silty clay [AR] of grey or yellowish colour due to oxidation, very stiff. The lower unit of Pleistocene sediments is composed by medium to coarse sand with gravel [SG], very dense, with the roof localised at + 6÷11 m below sea level. This stratum of sand with gravel rests directly upon the Pliocene formation of very stiff grey-light blue silty clay and clayey silt [APL], with the top at the depth of 44 metres from ground level. At the first 5/6 metres of the unit top, the stratum

Fig. 3 – Plan of the San Giovanni Line A-Line C interchange station.

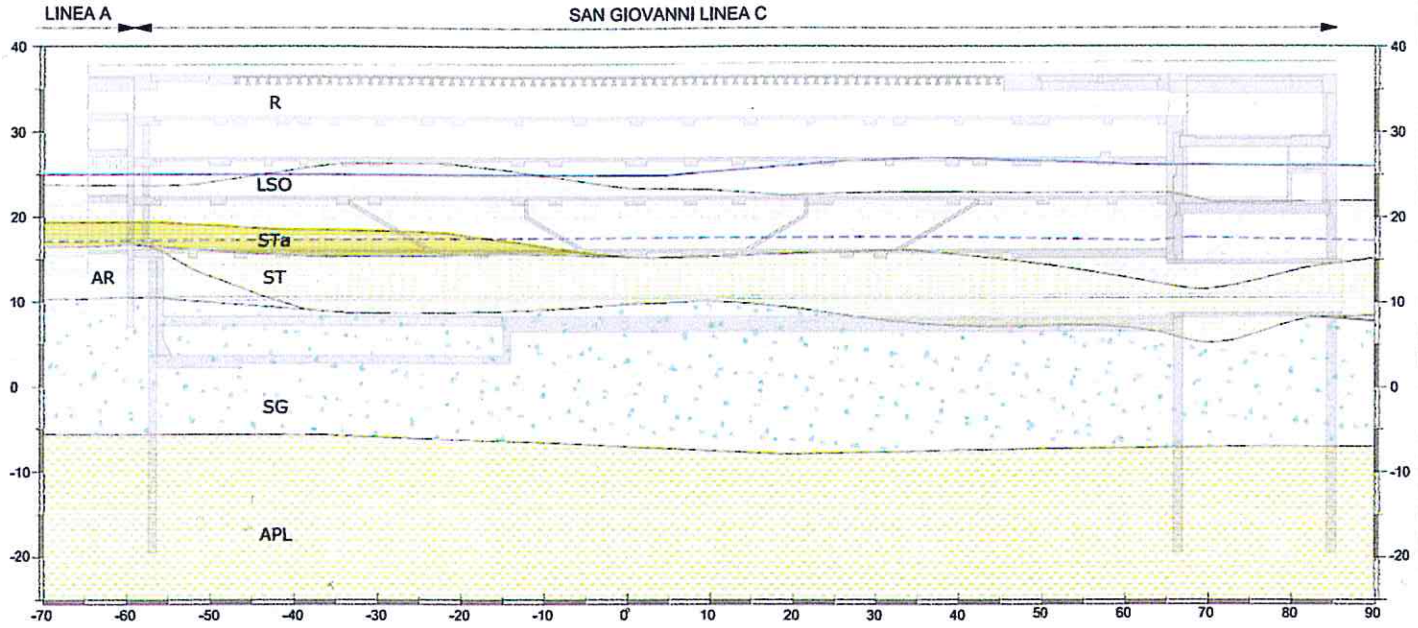

Fig. 4 – San Giovanni Station Line C - Geotechnical profile.

consists of some levels of fine sand, very dense, alternating with consistent clayey silt of different thickness no more than a decimeter thick; continuing downward, the facies becomes purely silty/clayey and highly stiff.

The design choices regarding the construction were strongly constrained not only by the pre-existing structures and the geological/geotechnical landscape, but also by what emerged during the archaeological surveys performed once the work site was begun: an unexpected presence of archaeological layers distributed in landfill down to depths of between 14 and 18 m, with a water table level at about 8 m below ground level (Fig. 5).

Following the results of the archaeological surveys, carried out before building the station's perimeter diaphragm walls and executing the jet grouting bottom plug, the Archaeological Authority (Superintendence) imposed the following construction constraints:

1. impossibility of performing consolidations from ground level without prior complete archaeological excavation;
2. need to carry out all the excavations by "archaeological procedure" down to "non-archaeological" layer.

These obligations, extended to all construction sites, required an overhaul of the Line C design in the historic centre of the

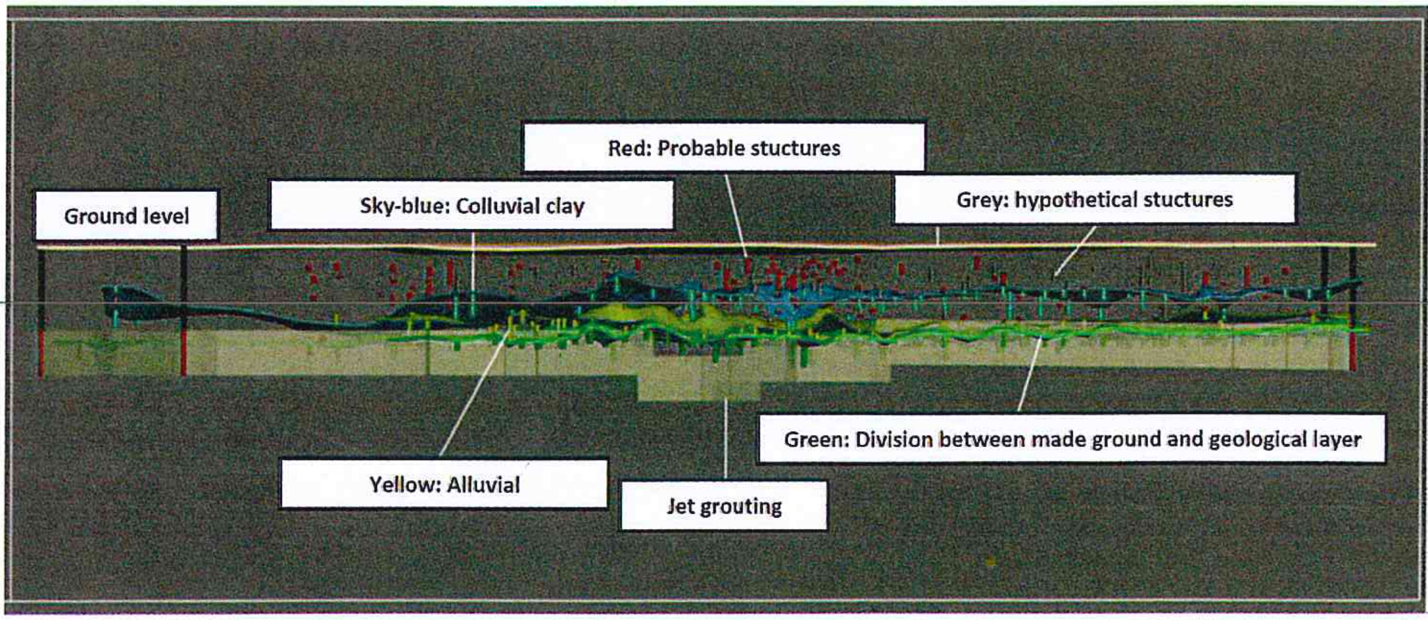

Fig. 5 – Three dimensional reconstruction of the archaeological surveys in the area of new San Giovanni Station.

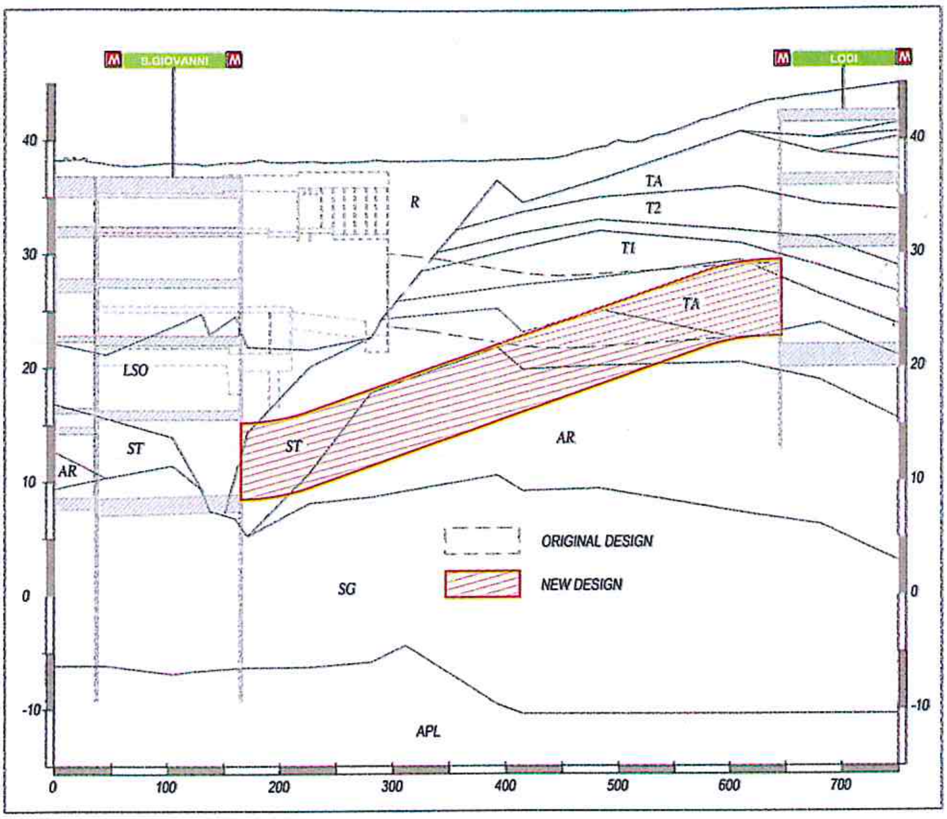

Fig. 6 – Geotechnical profile of Line C – comparison between the original and the new design.

city of Rome, starting from the San Giovanni station, to safeguard the archaeologically sensitive strata.

For the part of the line that runs from San Giovanni to Lodi, these obligations required, first of all, a plano-altimetric variation of the Line C alignment starting from the Lodi station (Fig. 6), deepening the line tunnels beneath the archaeological strata. This has resulted in the digging of natural tunnels to pass beneath the Line A existing station, abandoning the level left available in the design from the 1970s, on the slab above the Line A platform.

Secondly, the execution phases of the station were strongly constrained by the archaeology procedures, having to eliminate the excavation at the face typical of the "top-down" method with slabs cast against the earth.

The study of the new execution phases, in order not to lose the benefits of the "top-down" method - with the execution of descending slabs functioning as a strut to support the perimeter partitions - led to defining the following succession in construction which, for each slab, calls for:

1. excavation with archaeological method down to about 1.00 m beneath the slab's intrados;
2. execution of a perimeter concrete edging resting upon pockets made in the diaphragm and hung on the covering slab using Dywidag bars;
3. deepening the excavation by archaeological method for an additional 2.00 m;
4. execution of the slab with self-bearing prefabricated structures, and subsequent casting of completion.

These phases allow the excavation to be deepened by horizontal levels, thus preserving the ancient structures.

For the self-supporting structures in the casting phase, mixed reticular prefabricated beams were chosen, having sections varying between 80 and 100 cm, and spans of up to 20 m, along with ribbed girders, also self-supporting, with spans of up to 8 m and with a finished slab thickness of 40 cm (Fig. 7).

The handling of these prefabricated structures was carried out with a launching carrier hanging from the covering slab just built, by means of Dywidag bars (Fig. 8). This element has been installed and disassembled four times during the construction of the four underground slabs of the station.

The interaction with the existing station in operation has entailed a series of design and construction choices.

The most important is certainly the position of the Line C slabs. In order not to alter

Fig. 7 – The construction of an horizontal floor with self-bearing prefabricated.

Fig. 8 – The launching carrier used to move prefabricated structures and the perimeter concrete edging.

the balance with the horizontal actions, the slabs must necessarily be aligned with the existing ones of Line A, and have a thickness of no more than 1.00 m in order to guarantee the passage of the installations and the usability of the spaces.

The deepening of the excavation for building the Line C station also generated problems of carrying capacity for the Line A diaphragm partitions, as the partitions transmit the vertical loads to the ground's deep strata, given that there are no internal linings. To avoid this problem, it was deemed necessary to consolidate by jet grouting the stratum of sands and gravels at the foot of the diaphragm walls for the station's entire horizontal extent. This expedient makes it possible to build the Line C diaphragm walls adjacent to the Line A ones without altering the balance of the existing station.

To guarantee the transmission of the vertical loads over the long term, also after the execution of the tunnels passing beneath Line A, it became necessary to link the two structures with a reinforced concrete wall, connected to some Line C diaphragms and by means of grouting to the Line A partition.

Moreover, given the need to cross beneath the manufactured construction of the existing station by digging a natural tunnel abutting the foundation piles, it was necessary to assess the reduction of their lateral resistance. Because these were large-diameter piles (Ø2000) sunk into the extremely rigid stratum of sands and gravels, it was evaluated whether the carrying capacity at the end is preponderant with respect to the lateral carrying capacity. Moreover, the presence of a continuous foundation slab 40 cm thick guarantees a reduction in any displacement that may be generated.

Lastly, the two under-crossing tunnels cut the longitudinal diaphragm walls of the existing station from the side of the center section as well, thus generating a reduced vertical carrying capacity for these diaphragms. To avoid the problem, a wall beam was made, about 40 m long, connected to the Line A diaphragm walls at the existing station's platform level. This structure, resting upon 3 plinths with preloaded micro piles, has the function of transferring all the vertical loads of the longitudinal alignment of the partitions to the deep layers of ground beneath the line tunnels.

As the traffic of Line A and/or the station could not be interrupted while the tunnels were being built, a track support system, for both directions, was provided for within the platform level, built with a continuous metal deck with two spans 20 m in length, resting on micro piles (Fig. 9).

In compliance with the regulations in force, having altered the existing station's foundation structure, as described above, it became necessary to verify seismic safety and to perform the consequent adjustment work.

Since this is an underground structure, the structural elements under flexional stress by the seismic event are the perimeter diaphragm walls, which in correspondence with the two inter-levels require being reinforced.

The problem of possible "hammering" between the two structures, due to the phase opposition of seismic waves, was solved by linking the two structures by means of the external wall to the Line A diaphragm walls.

Another challenge faced has been the underpassing of the existing Line A San Giovanni Station with two tunnels, each 40 meters in length, excavated by conventional mining, using a variety of consolidation techniques including chemical and cement injections and artificial ground freezing (Fig. 10).

The tunnel excavation is inside two different geological layers from the Pleistocene Age; the top of the tunnels is inside clayey silts and the bottom is in fluvial deposit composed of gravels and sands. The hydraulic head above the tunnel top is approximately 10 m.

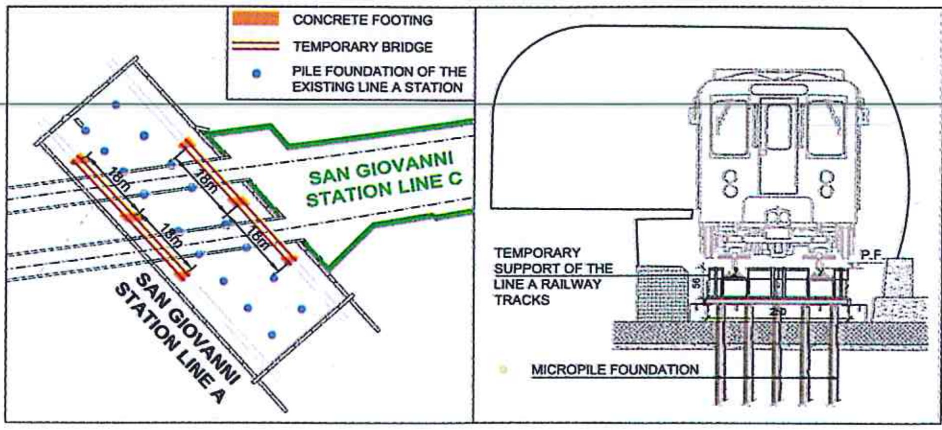

Fig. 9 – Plan and cross section of the temporary steel bridges.

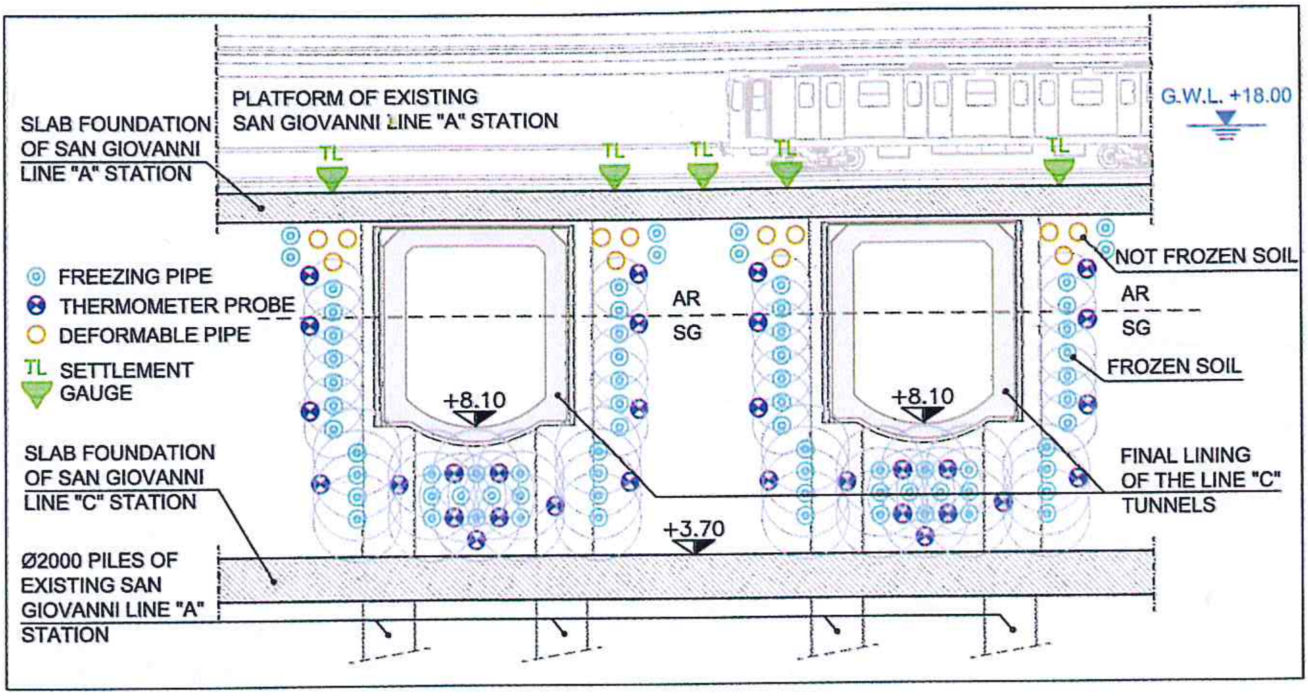

Fig. 10 – Cross section of the Line C tunnel underpassing the existing Line A station.

The choice of conventional mining methods derives from the presence of the slab and the Ø2000 foundation piles of the existing Line A station which, as they are placed at a net interaxis of approximately 5 m, made it impossible to continue the mechanized excavation with TBM (diameter 6.70 m). The choice of the freezing technology, on the other hand, is connected with the impossibility of carrying out consolidations from above, given the presence of the existing station and, above all, with the heterogeneous nature of the soils to be excavated which, for about 2/3 of the tunnel section, are sands and gravel, with rather high permeability, at times even exceeding 10^{-4} m/s.

The technology of artificial ground freezing consists of freezing the water within a volume of soil, in accordance with a known geometry, thanks to heat exchangers in which low-temperature liquid circulates. This extracts the heat from the ground and dissipates it to the outside. The particular complexity of the design geometries required the use of a mixed system employing nitrogen in the initial phases of freezing, to reduce the time required to form ice wall by having to treat significant volumes of ground, and brine in the maintenance phase, to control the growth of the ice wall with time, thus reducing the deformation induced on the existing slab of Line A.

Placed around each tunnel to be excavated were 36 freeze pipes circulating refrigerants, and 15 temperature probes for the continuous and real-time monitoring of the development of the ice wall. The distances between the freeze pipes vary from about 75-80 cm on the sidewalls to 3 m in correspondence with the invert due to the presence of the piles; the average length is about 36-39 m. To respect the design's geometry and interaxes for their entire length, the drilling operations were guided using the TDDT (Trevi Directional Drilling Technology) system. The average design temperature is -10 °C and the ice wall to be made around each tunnel has a thickness of about 80 cm at the sidewalls and approximately 3 m in invert.

The freezing activation and, similarly, the excavation of the two tunnels took place at different times. In both cases, the nitrogen activation lasted for about 40 days, and afterward the system was converted to brine. The nitrogen consumption for each tunnel was about 1500-1700 l/m³, in line with the design forecasts, based on the interpretation of the data of a specific field trial.

In each tunnel (Fig. 11), it was necessary re-profiling of two/three piles interfering with the train's gauge, after the accurate reconstruction of the real gauge following the tachometric survey.

Fig. 11 – Tunnel excavation.

Fig. 12 – A view of the Roman reservoir found during the archaeological excavation.

Fig. 14 – San Giovanni Station - "Stratigrafo" printed on the glass-facings.

Fig. 13 – A reconstruction of the area carried out by the Archeological Ministerial Office.

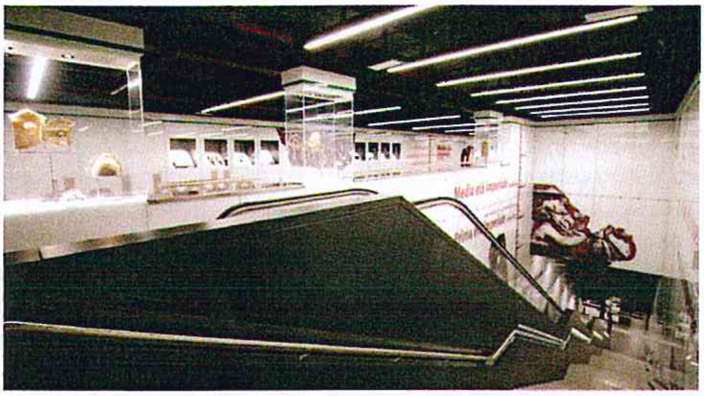

Fig. 15 – San Giovanni Station - A view of the exhibition at the corresponding level.

The enhancement of the archaeological context: the "Museum station"

The excavation of San Giovanni Station was a rich opportunity of new and important acquisitions for the knowledge of the history of Rome. It was a unique opportunity for the archaeologists because the archaeological excavations rarely reach a similar depth in urban areas.
In San Giovanni station, the excavation reached about 30 m from the ground level and it crossed many archaeological layers that allowed a chronological reconstruction through the ages. The excavation phases were a 'long time travel' that started with our time at the ground level and reached the prehistoric times crossing modern age, middle age, imperial and republican ages. The most important structure found during the archaeological excavation (Fig. 12) was a big reservoir of late Roman age with dimensions of 35 m in width and 70 m in length (Fig. 13). Consequently to this and to other finds, the Archeological Authority got to change San Giovanni station architectonic design in order to add value to the archaeological context at the end of the excavation.
Thus Metro C, with Roma Metropolitane supervision, designed and realized a permanent exhibition design of the archaeological findings with the cooperation of a group of professors and architects belonging to the Architectural Department of University "La Sapienza" of Rome, led by Andrea Grimaldi and Filippo Lambertucci.
They based this design on a long tale and projection in the history of Rome using many graphic elements such as images and texts printed on glass-facings and some special strategic establishments for the exhibition of a short selection of remains carried out in about 40.000 findings.
Because this exhibition is inside an underground station and not in a museum, high perceptibility, fast comprehension and visual comfort are three important characteristics of the design.
The most important symbol of this projection is a "stratigrafo" printed on the glass-facings, that consists of a vertical scale where passengers can read at the same time the true depth in meters from the ground level and the remarkable events in San Giovanni area and in the whole city of Rome (Fig. 14). Also, many large titles printed on glass-facings suggest the meaning of specific exhibitions of remains in specific areas of the station and they give to the passengers the key of interpretation what they see (Fig. 15).
The horizontal levels of the station opened to the public – the first and the third level with Line A interchange and the platform – match significant levels of sequence of the historic events. In fact the most significant and known remains were found at the depth of the interchange level with existing Line A. At this level, we found a big complex of hydraulic and agricultural equipment belonging to a large farm of imperial age

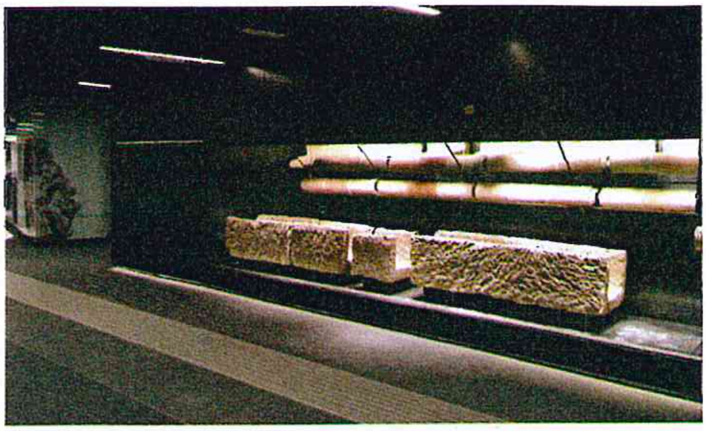

Fig. 16 – San Giovanni Station - A view of the exhibition of pipes and hydraulic equipment at corresponding level.

Fig. 17 – San Giovanni Station - A view of the exhibition at the platform level.

on the edge of the town. The big reservoir was found in this area, so the design considers the trace of the perimeter walls of this structure signed by a different type of floor and also the show of a large number of pipes and hydraulic equipment found during the excavation (Fig. 16).

At the end of this long travel, the passengers arrive to the platform level. This level matches the prehistoric time and the exhibition is characterized by an abundant flora and a rare human involvement. For this reason, at this level, there are only images printed on the glass-facings (Fig. 17).

The downtown section and the safeguard of monuments

The T3 stretch is presently under construction and it will underpass the historical center of Rome. T3 stretch starts with San Giovanni station and it is about 3 km in length. It includes two stations (Amba Aradam and Fori Imperiali) and 2 shafts with ventilation systems (Shaft 3.3 and shaft 3.2).

The tunnels are going to be excavated by 2 EPB TBMS, with a cut diameter of 6.70 m, at a depth between 30 m and 60 m.

The T3 stretch of Line C is characterized by the presence of historic buildings and monuments of great value such as Colos-

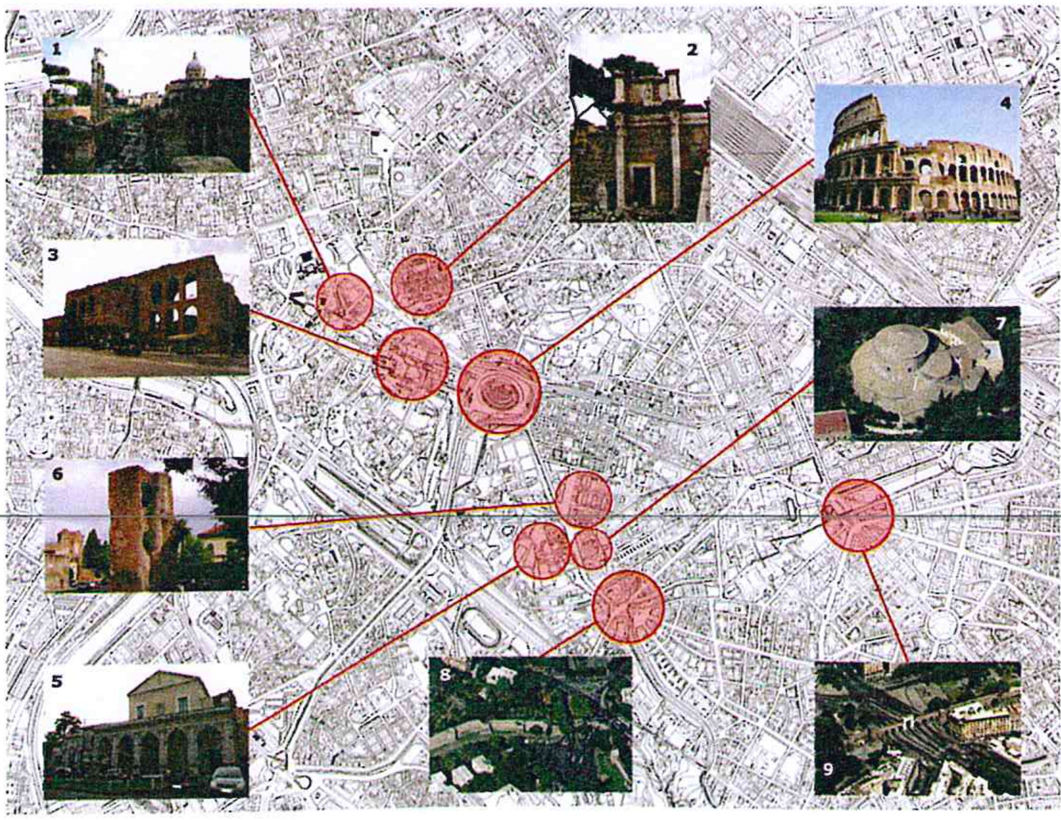

Fig. 18 – A plan with monuments underpassed by T3 stretch.

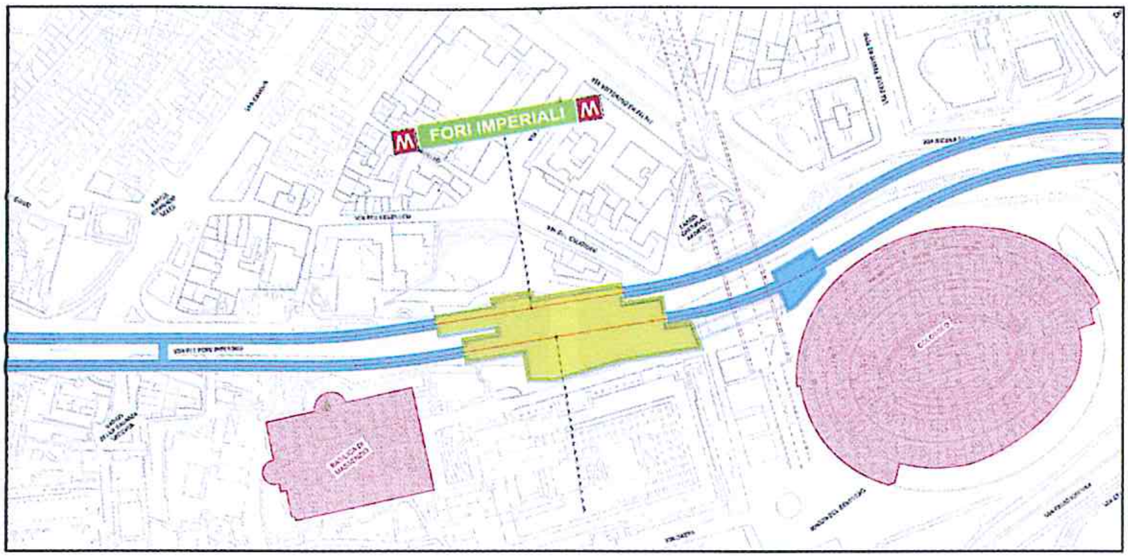

Fig. 19 – Plan view of the Basilica and the running tunnels together with the location of the Fori Imperiali Station.

seo, Chiesa di Santo Stefano Rotondo and Basilica di Massenzio (Fig. 18).

The Historical Centre of Rome is a UNESCO World Heritage site and in order to safeguard all the monuments a specific Scientific Technical Committee (STC) was constituted, including world famous professors. The aim of this Committee was to ensure high quality research methods and to analyze potential interactions between the new line and the historical monumental heritage.

The Committee coordinates and supervises the activities of working groups of specialists. These perform a range of activities aimed at defining the status of 40 valuable historical buildings (including "Palazzo della Cancelleria", "Palazzo Venezia", "Palazzo Sforza Cesarini", the Church of "Sant Andrea della Valle") and 13 monuments (including the Colosseo, Basilica di Massenzio, Colonna Traiana e Vittoriano) in relation to the construction of the new underground.

The 5 work teams consisting of university professors and specialists operate in the following fields: Geology, Geotechnical engineering, Restoration and preservation, Structural engineering, Monitoring system.

The interaction studies, developed by the team over 2 years, defined a methodological approach that can be divided in 3 important steps:

a. preliminary studies that consist of historical study and identification of the construction stages, identification of the type, the materials and the geometry of the foundations, identification of the material characteristics and of the building technologies, structural and crack pattern survey and geometrical survey;
b. interaction analyses that consists of level 1 and 2 geotechnical analyses and structural analyses;
c. drawning up of guide lines for the design of the most appropriate geotechnical and structural protection measures and the monitoring system.

This methodological approach was used to interaction studies between line and all monuments of the historical center of Rome in T3 and T2 stretch. The aim of the interaction studies is to evaluate the possible effects on the buildings, induced by the displacement field generated by tunnelling and deep excavations.

The evaluation of the expected damage was carried out with reference to the classification of damage by Burland (1995), based on the combination of the computed horizontal tensile strain and deflection ratio.

At a first level, simplified analyses were performed using the semi-empirical method and neglecting the stiffness and the weight of the buildings. The resulting displacement field was applied by the structural engineering group to a 3D linear elastic or non-linear finite element model of the structure under examination. Based on the results of the geotechnical and structural evaluations, the study ended if the damage was considered negligible, or continued to a higher level of complexity (Level 2 analyses).

At this second stage, the interaction between the tunnels and the historical buildings was studied through full soil-structure interaction analyses, performed in both 2D or 3D conditions, accounting for the stiffness and weight of existing buildings and considering possible long-term effects. The computed displacement filed was applied again to the structural model and damage was re-evaluated, independently, by both groups. Depending on the computed results, either damage was considered acceptable, or prospective remedial techniques must be designed.

The remedial techniques are geotechnical or structural. The geotechnical active measures are compensation grouting injections, the geotechnical passive measures are cross walls, instead the structural active measures are bars or steel ropes and the structural passive measures are temporary supports.

The basilica di Massenzio case-history

At the end of the T3 stretch, tunnels run along via dei Fori Imperiali, very close to the Colosseo and the Basilica di Massenzio (Fig. 19). The latter is a very interesting example to illustrate the approach that was adopted in the study. In fact, the Basilica is a particularly heavy structure, with significant contact stress transferred to the soil by the foundations that consist of simple

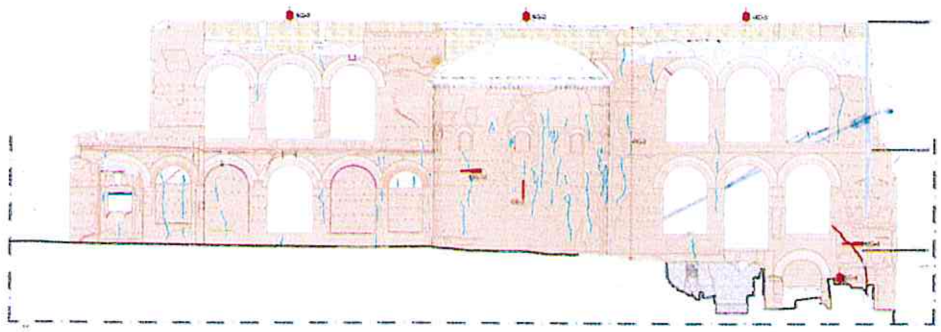

Fig. 20 – Structural and cracks patterns survey.

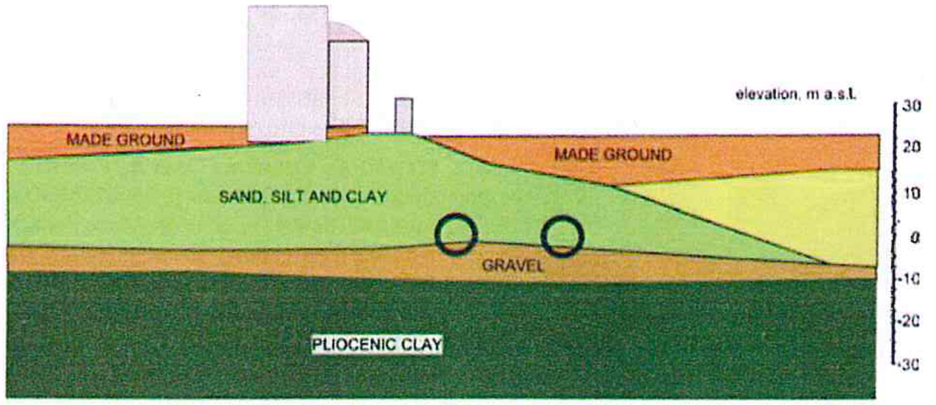

Fig. 21 – Stratigraphic profile along the central transversal section.

extension of the bearing walls, with a very limited widening.

The preliminary studies started with the identification of construction stages and the research of the bibliographical sources with an important collection of photographic documentation. Construction of Basilica began on the northern side of the forum under emperor Massenzio in 308, and was completed in 312 by Costantino I, after his defeat of Massenzio at the battle of Ponte Milvio.

Also the preliminary studies examined the structural failures and subsequent historical reinforcements, the geometrical survey, the structural and crack pattern survey and the material characteristics and the construction technologies with diagnostic investigations (Fig. 20).

An important phase of preliminary studies was the geotechnical investigations to define the ground conditions. The geotechnical characterization of the foundation soils of the Basilica was undertaken using the results of site and laboratory tests carried out during several geotechnical investigation campaigns. The tunnels near Basilica di Massenzio are mainly contained into medium and fine grained soils of the Paleotevere (Fig. 21).

Following the methodological approach described above, Level 1 and Level 2 analyses were carried out (Fig. 22). Before the construction of the tunnels, according to Burland's classification, the structure already is in a state of slight damage, and also if the category of damage is not worsened by the work, it was decided to design structural reinforcements.

The design of the structural reinforcements (Fig. 23) consists of restoration of the bricks facings with the use of fibers and structural injections and some longitudinal and transversal dywidag bars to reinforce the structure with also a couple of steel wire ropes around the apse. Also the design consider some structural reinforce with temporary supports (Fig. 24).

A complex monitoring system was developed and implemented with the following aims: a) check during construction of the design prediction; b) validation of the models adopted for the interaction analyses and calibration of the physical and mechanical parameters; c) instrument of the

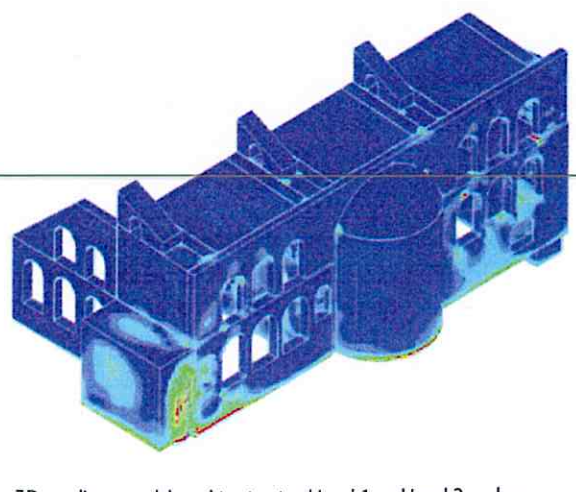

Fig. 22 – 3D non linear model used to structural Level 1 and Level 2 analyses.

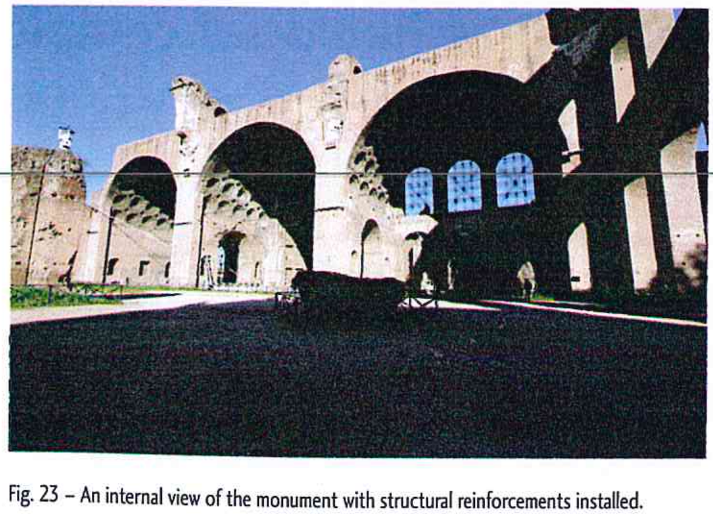

Fig. 23 – An internal view of the monument with structural reinforcements installed.

Fig. 24 – An external view of the monument with the temporary supports installed.

Fig. 25 – An internal view of the monument with the monitoring instrumentation installed.

observational method for the activation of the compensation measures of the settlements. The monitoring systems consist of structural monitoring, geomatic monitoring and geotechnical monitoring, with different instrumentations (Fig. 25).

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Riassunto di:
L'implementazione di un'infrastruttura sotterranea in contesti archeologici complessi: alcune esperienze di progettazione e costruzione della nuova linea C della metropolitana di Roma

A. Sciotti
Roma Metropolitane S.r.l; Responsabile del Procedimento della Linea C

E. Romani
Metro C S.c.p.a.; Responsabile della Progettazioneine

M. D'Angelo
Metro C S.c.p.a.; Direttore Generale

La nuova Linea C della metropolitana di Roma attraversa il centro storico della città e s'inserisce in un'area ad alta densità di monumenti e di pre-esistenze archeologiche, al di sopra e al di sotto dell'attuale livello urbano. La corretta gestione del tema archeologico sta rivestendo un ruolo fondamentale nell'implementazione di tale infrastruttura. Il focus di quest'articolo è su alcuni aspetti correlati a tale tema e trattati nella fase di progettazione e di realizzazione: la definizione delle modalità di completamento delle indagini archeologiche durante la fase costruttiva delle opere, le soluzioni individuate per la realizzazione della Stazione San Giovanni e per la valorizzazione del contesto archeologico ricostruito, l'approccio metodologico adottato per la salvaguardia dei monumenti.