Galleria Olmata, from survey to construction: an integrated design approach for the renewal of railway tunnels

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ABSTRACT: RFI (Rete Ferroviaria Italiana - Italian Railway Network) has been undertaking for several years an intense activity of maintenance and renewal of the heritage and strategic infrastructure. ETS has been in charge of the survey and the design for the renewal of Galleria Olmata (Olmata Tunnel), part of the Scandinavian-Mediterranean Corridor which represents the north-south axis of the Trans-European Transport Networks (TEN-T). The project required: the widening of the clearance to ensure the strengthening of the railway, the resolution of the leakages, the mapping and backfilling of the cavities along the line, and the execution of the works with respect to the requirements of a working line

KEYWORDS: Maintenance, Technical innovation, ARCHITA, Sustainable and strategic use of underground space, Integrated design, Retro BIM, BIM, FEM, mobile mapping,

1. INTRODUCTION

RFI (Rete Ferroviaria Italiana - Italian Railway Network) has been undertaking for several years an intense activity of maintenance and renewal of the infrastructure heritage. ETS has been in charge of the survey and the design for the renewal of Galleria Olmata.
Galleria Olmata is almost 1 km long, from pk 37+760 to pk 38+713 of the railway line Roma-Napoli. The tunnel is part of the Scandinavian-Mediterranean Corridor which is the north-south axis of the Trans-European Transport Networks (TEN-T).

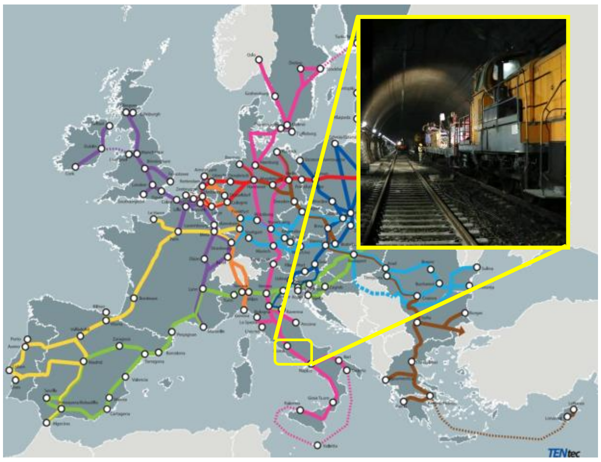

Figure 1 Trans-European Transport Networks (TEN-T). In violet, the Scandinavian-Mediterranean Corridor and, in yellow, the railway line Roma-Napoli with the detail of Galleria Olmata

The project required: the widening of the clearance to ensure the strengthening of the railway, the resolution of the leakages, the mapping and backfilling of the cavities along the line, and the execution of the works with respect to the requirements of a working line.
ETS has developed and deployed ARCHITA, a multi-dimensional survey system equipped with a laser scanner, linear cameras, thermal cameras, and ground penetrating radar to survey the geometrical and structural conditions of the tunnel without frequent and long stops of the traffic. ARCHITA is coupled with an extensive conventional investigation campaign.
The paper shows the methodology of surveying the tunnel structures (ARCHITA), verifying the clearance conditions, designing the reinforcement works and the milling of the existing lining with the support of FEM analysis, planning of the construction activities, integrated approach (BIM) in all the stages.

2. TUNNEL SURVEY

2.1 Scope

In order to achieve the project requirements, it is necessary to get an adequate level of knowledge of the actual condition, geometrical and mechanical, of the tunnel and the subsoil. An investigation campaign is carried out setting the following objectives:
- Condition assessment of the tunnel lining and internal structures;
- Characterization of the geotechnical-geomechanical context;
- Geometric survey of the existing infrastructure to evaluate possible interferences of the existing lining with the new trains;
- Hydrogeology and groundwater along the tunnel.

2.2 ARCHITA

To achieve its intended objectives with respect to the traffic of an existing line ETS has developed and deployed ARCHITA, a multidimensional mobile-mapping system.
ARCHITA consists of linked and integrated technologies on a bimodal vehicle to work both on-road and railway line. The RAIL configuration (Figure 2) performs continuous surveying activity with an average speed of 15-30 km/h.

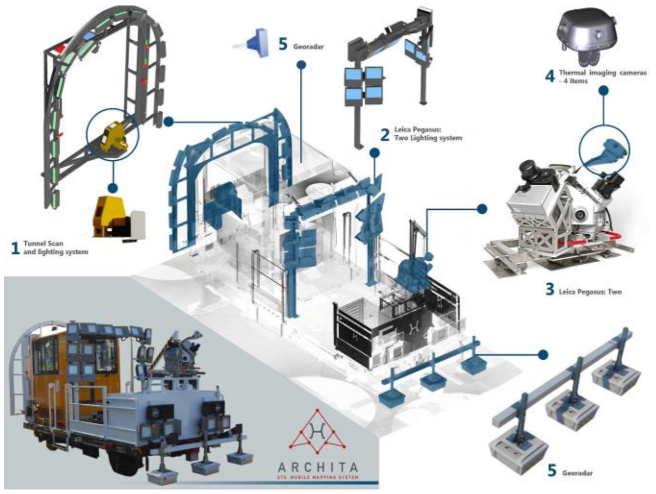

Figure 2 ARCHITA system (ETS, 2019)

The ARCHITA system consists of:
- Laser Scanner to acquire 3D point cloud with a resolution of 1 mm (longitudinally), 2 mm (transversally) and 1 mm (radially);
- Tunnel Scan to take high-resolution photos (1 pixels/mm) of the tunnel lining, detecting the components and the conservation state;
- GPRs to survey the ballast thickness, status and humidity (3 antennae), and the lining thickness, defects and cavities (1 antenna);
- Thermal Imaging to detect humidity on the lining.
The different tools are integrated and linked each other, allowing to acquire multiple information for every single point simplifying the acquisition. Engineering experience and judgment are fundamental when processing and interpreting the huge amount of data back in the office, especially when using multidimensional surveying tools.

2.3 Traditional in-situ investigation campaign

The tunnel has been involved in an extensive in-situ traditional survey with destructive and non-destructive tests. The survey in the tunnel took place between October 2017 and April 2018. Surveying inside the tunnel was carried out alternately on both tracks about every 40-50 m. Surveying inside the tunnel was distributed in a total of 16 sections.

The survey on the soil surface took place in two different time phases: the first was performed between April and May 2018 and the second in September 2018.

Figure 3 shows a layout of the investigated verticals and sections. Geophysics from the surface was not performed due to the inability to access the surrounding lands. Figure 4 shows the coring activity inside the tunnel.

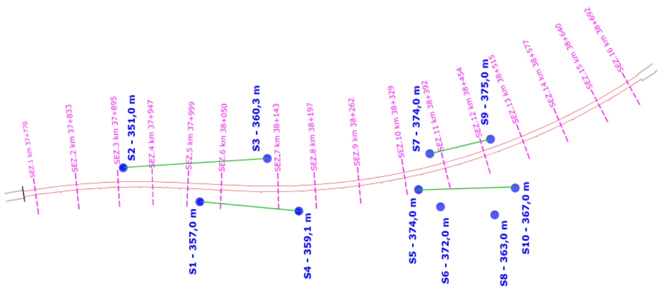

Figure 3 Layout of the boreholes. In violet, from the tunnel, and, in blue, from the ground surface

Figure 4 Coring activity inside Galleria Olmata

2.4 Main outcomes

The geotechnical-geomechanical context is composed of volcanic formations, ranging from pyroclastics of medium-low consistency to tuff with good mechanical characteristics. The investigations revealed no presence of groundwater and the tunnel leakages are consequences of meteoric events.

The geotechnical-geomechanical characterization is carried out through laboratory tests (Direct Shear for the low consistent rock and soil part; Uniaxial Compressive Strength for the rock part) and in-situ tests (SPT for the surface soil). Table 1 summarizes the characterization with a Mohr-Coulomb failure criterion.

Table 1 Characteristic geotechnical/geomechanical parameters

Geotechnical Unit	Material	γ_{sat} [kN/m^3]	c' [kPa]	ϕ' [°]	E' [MPa]
GU1	Pyroclastics	14.5	5	30	20
GU2	Tuff	18.0	30	35	45

The lining of the tunnel is masonry with squared tuff blocks and mortar joints of the pozzolanic matrix.

In Figure 5, the thickness values obtained along the tunnel from the survey are shown. The punctual values obtained from destructive tests allowed to carefully validate ARCHITA georadar results and obtain a profile of the thicknesses for the entire tunnel. The presence of a flat foundation is detected (no invert). The lining thickness differs of 40-80 cm, between crown and sidewalls, and 53-110 cm between slab and sidewalls. Table 2 lists the detected thicknesses of the lining and the rock beyond.

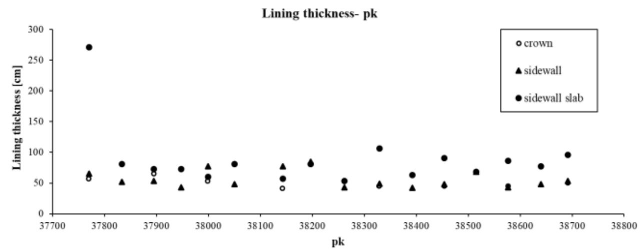

Figure 5 Thickness of the lining along the tunnel

Table 1 Thickness range [cm] of the lining *SW=sidewall SH=shoulder

	First track		Second track	
	SW	**SH**	**SW**	**SH**
Max Lining Total thickness	40-45	45-50	40-45	40-45
Min Lining Total thickness	75-80	70-75	85-90	85-90
Weathered Lining thickness	5-35	5-30	5-30	5-40
Weathered Rock thickness	5-40	10-30	10-40	5-40

In Figure 6, the actual stress state vs. the elastic limit stress of the masonry lining are shown. The values are measured with single and double flat jack tests on the sidewalls of both the tracks. The results show low working load (around 13% to 33%) of the masonry, probably due to the good mechanical characteristics of the subsoil. Detected service stress value is on average around 0.5 – 0.6 MPa.

Double punching and compression tests are performed in order to determine the compressive strength of the mortar and rock.

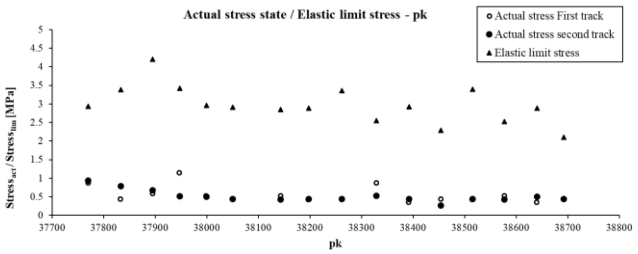

Figure 6 Stresses measured in the lining along the tunnel

The measured thickness of the subgrade is on average 50 cm (Figure 7), with a moderate state of conservation, slightly polluted by fine particle material, mainly wet, between dry-humid and humid at the base with a highly wavy surface (maximum variation around 10-15 cm). No critical zones are identified in the subgrade (Figure 8).

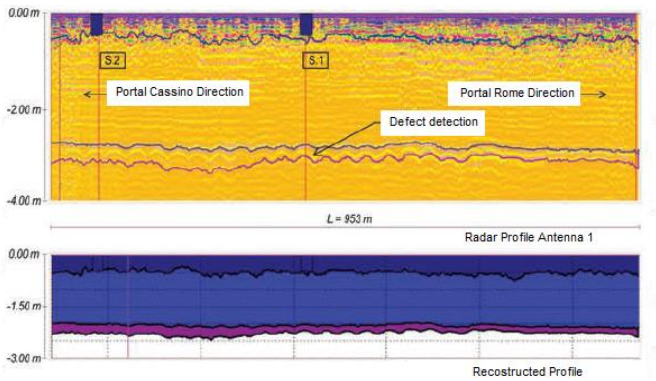

Figure 7 Ballast from pk 37+760 to pk 38+713: interpretation of GPR survey of ARCHITA (Antenna 1)

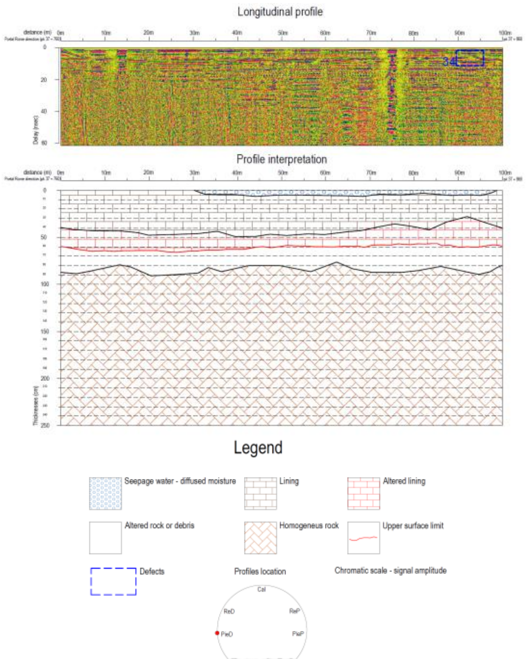

Figure 8 Sidewall from pk 37+760 to pk 37+869: GPR survey of ARCHITA (on the top) and interpretation (on the bottom)

2.5 Critical aspects

ARCHITA geo-radar and photographic surveys allow detecting critical issues of the structure (Figure 9 and Figure 10). For the tunnel lining, it concerns mainly: humidity and leakages, masonry alteration due to the erosive effect of the water. No groundwater table is detected and the leakages are an effect of meteoric events.
The state of the lining shows slight deterioration and some small alterations in the humid areas. The situation is confirmed by both the endoscopic surveys and coring.

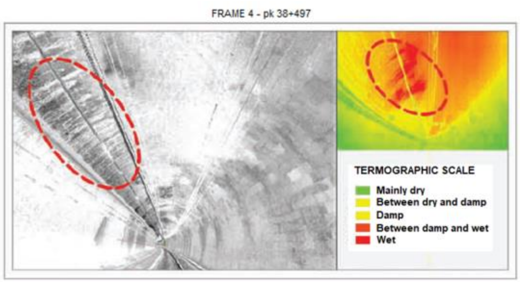

Figure 9 Thermal images to investigate the humidity of the lining

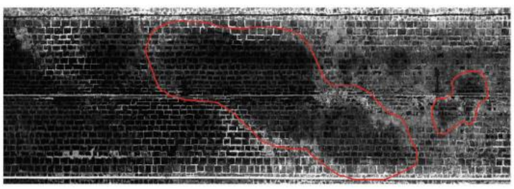

Figure 10 HD images to investigate the humidity of the lining

3. MILLING FOR WIDENING OF THE CLEARANCE

3.1 Scope

The clearance adjustment is performed by milling the existing lining. A dynamic clearance analysis is carried out by overlapping the clearance of the new trains (PC80) with the existing clearance of the tunnel. The analysis allows a minimization of the impact of the milling activities.
The design phase is divided into:
- The use of an innovative surveying system for input data acquisition (ARCHITA);
- Reconstruction of the 3D railway line geometry and alignment.

3.2 Digitalization and Retro BIM

The multidisciplinary nature of the project led to the development of a customized OpenBIM Workflow, with the aim of improving: the control over the entire design process, the potential of the acquired data and consistency of the database.
The process is depicted in Figure 11. The parametric sections relative to the actual state of the lining and of the subgrade are reconstructed starting from the geometries of the railway line (i.e. Point Cloud and 3D CAD) and the qualitative data (i.e. stratigraphy and thicknesses). The sections are extruded following the tunnel alignment. The characteristic 3D polylines extracted from the Point Cloud are used as a guide.

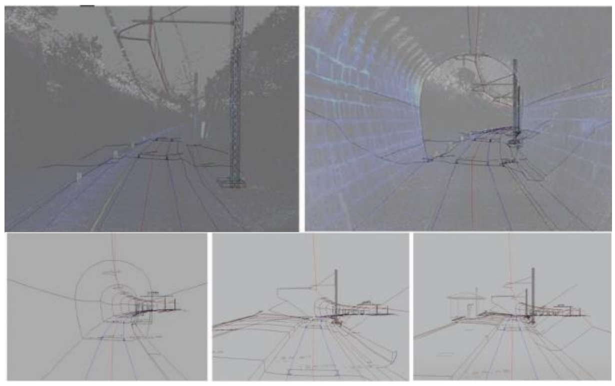

Figure 11 Transition from 3D point cloud (ARCHITA) to digitalization (CAD 3D and IFC).

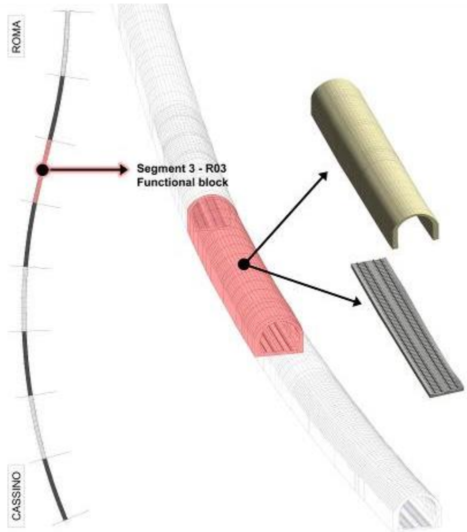

Figure 12 R03, from pk 37+960 to pk 37+913: decomposition of the As-Built models in Functional Blocks and Disciplines

The different Information Models follow a breakdown of the project according to functional blocks subdivided also by disciplines, each one belongs to specific technicians and it's coordinated through a Federal Model located in the ACDat main file. The methodology allows the creation of a virtual office, where a network of authors speaks the same language and join the process in a controlled way.

3.3 Clearance analysis and design of the milling

The OpenBIM Workflow allows automating the clearance interference analysis (Figure 13). The planimetric and altimetric layout is readjusted to reduce the volume of the geometric interferences between the limit clearance and the geometric section of the tunnel. The operations involve lowering the rail level of the tracks and milling the tunnel lining in the areas where the interference is detected.
In the sections where the lowering of the rail is greater than 5 cm, the ballast is replaced with a new 68 cm package. The milling thicknesses include 5 cm along all the tunnel to allow the intrados renovation of the masonry.
Previous to the milling operations, preliminary consolidations are carried out, such as injections on masonry lining, injections on the surrounding subsoil and the installation of GFRP bolts. In order to limit

the static-deformation effects on the tunnel, all the operations are performed with a span of 1 m.

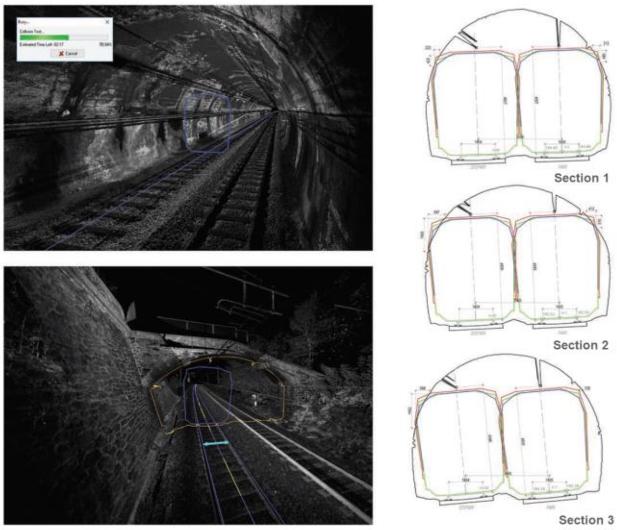

Figure 13 Clearance analysis along the alignment

After that, the milling process and further consolidation are carried out according to the following criteria:
- for geometrical interferences greater than 25 cm, milling of about 70 cm is intended with the installation of a new lining composed of steel ribs and shotcrete;
- for geometrical interferences between 5 and 25 cm, a consolidation is considered by installing steel bars connected each other with a steel beam;
- for geometrical interferences below 5 cm, additional interventions are not considered with respect to the preliminary consolidations.

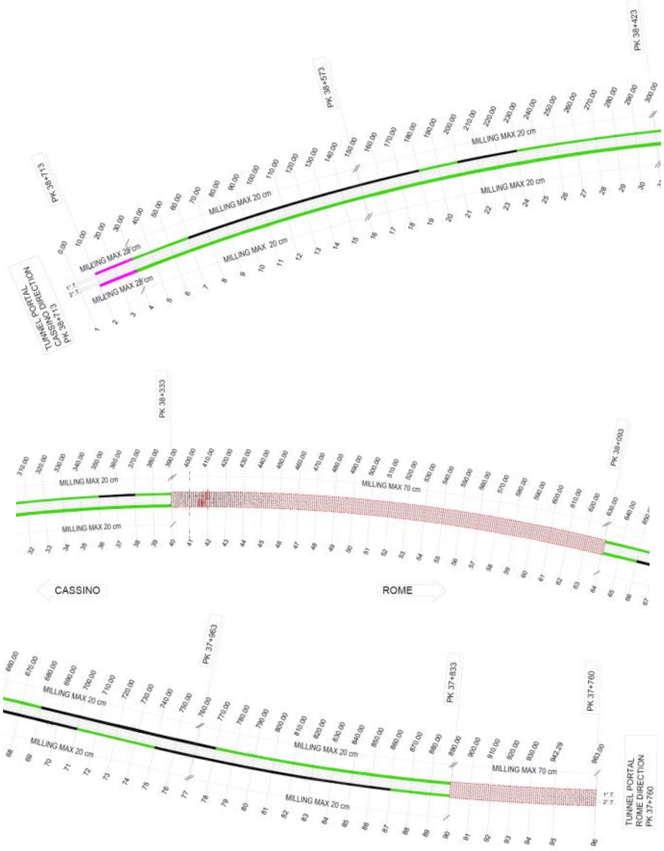

Figure 14 Layout of the milling activities

4. REINFORCEMENTS

The project interventions consist of different techniques involving both the structures and the soil. The activities are divided into different time phases, in order to minimize the interference with the working line. The works are done during night time (Scheduled Interruptions in Hours). If not possible, for executive reasons, works are conducted with total blockade of the line.

4.1 Typological sections

Based on the importance of the geometric interferences, the interventions can be divided into 3 macro-sectors, described below, with the relative typological sections applied (i.e. A0, A1, A2). In Figure 15 and Figure 16, all the possible working phases are depicted, following a non-sequential order as they represent different type sections.

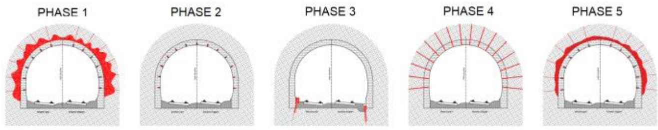

Figure 15 Phase 1 (Filling of cavities), Phase 2 (Reinforcement of the lining), Phase 3 (Micropiles, A1-A2), Phase 4 (Radial GFRP bolts, pre-milling), Phase 5 (Sealing)

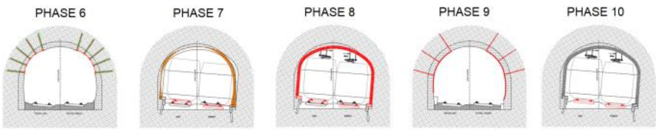

Figure 16 Phase 6 (Light Milling and radial rockbolts, A0-A1), Phase 7 (Heavy Milling, A2), Phase 8 (Steel ribs, A2), Phase 9 (Drainage system Steel ribs, A2), Phase 10 (Final configuration)

The A0 section is applied between km 37+963 - 38+093 and km 38+423 - 38+573. The A1 section is applied between km 37+833 - 37+963, km 38+333 - 38+423, and km 38+573 - 38+713. The A2 section is applied between km 37+760 - 37+833 and km 38+093 - 38+333.

In the following, the phases are described in details:

- Phase 1 (A0, A1, A2): consolidation injections on the soil and lining structures of the tunnel;
- Phase 2 (A0, A1, A2): consolidation injections on the lining structures of the tunnel;
- Phase 3 (A1, A2): construction of a single micropiled wall on the side of the track affected by the lowering of the rail line, with micropiles having a drilling diameter of 225 mm, a steel tube of 168.3 diameter and a thickness of 12.5 mm, a longitudinal spacing of 1 m, SGI technique (Single Global Injection) and a vertical inclination of 10°. Construction of a R.C. curb of 40x60 cm connecting the micropiles;
- Phase 4a (A0, A1): installation of GFRP bolts of 32 mm diameter, drilling diameter of 50 mm, 4 m length and spacing of 1 m, for the consolidation of the excavation perimeter;
- Phase 4b (A2): installation of 8 + 8 radial GFRP bolts of 32 mm diameter, drilling diameter of 50 mm, 4 m length and spacing of 1 m, for the consolidation of the excavation perimeter;
- Phase 5 (A0, A1, A2): injections in the soil for water sealing using polyurethane resins;
- Phase 6 (A0, A1): milling of the tunnel lining in alternate zones and thicknesses of about 15-20 cm and installation of 5 + 5 radial B450C steel bars with improved adherence acting as definitive anchorage with a diameter of 32 mm, perforation diameter of 50 mm, 4 m length and spacing of 1 m. Connection through a steel beam and fixing plates;
- Phase 7 (A2): milling of part of the tunnel lining of about 0.7-1.0 m;
- Phase 8 (A2): construction of a new tunnel lining consisting of 2 coupled IPE 160 beams acting as ribs, incorporated within a shotcrete layer with a minimum thickness of 20 mm;
- Phase 9 (A0, A1, A2): drilling and insertion of PVC pipes for water drainage behind the lining. The positioning of vibrated r.c. channels at the foot of the sidewalls;
- Phase 10a (A0): excavation below the tracks, affected by the lowering of the rail line, by milling the tuff layer up to a maximum of 5 cm;

- Phase 10b (A1): excavation below the tracks, affected by the lowering of the rail line, by milling the tuff layer up to a maximum of 85 cm (70 cm for the new ballast and 25 cm for lowering);
- Phase 10c (A2): excavation below the tracks, affected by the lowering of the rail line, by milling the tuff layer up to a maximum of 95 cm (70 cm for the new ballast and 35 cm for the lowering);
- (A0, A1, A2) Masonry coating 5 cm thick with electro-welded mesh, shotcrete and mortar. The positioning of the new ballast and the overhead line.

4.2 Design and FEM analyses

The project phases and the construction methodology are modelled with PLAXIS 2D, a commercial FEM software for geotechnical analysis.
The starting point is to reproduce the actual in-situ state in terms of working stresses and characteristics of the lining obtained from surveying. The calculation simulates the stress-strain behaviour, supplying results that comply with the current norms and codes, allowing to proceed with the design of the interventions and the permanent structures.
The modelling of the actual state is carried out by applying the convergence-confinement method, coupling the retrofitted characteristic curve and convergence-distance curve (Figure 17). The methodology is completely valid for deep tunnels, like the case of almost all the Galleria Olmata.
Analysing the characteristic curve, an elastoplastic behaviour of the cavity emerged, with a linear elastic trend with release factors of about 0.7-0.8. Furthermore, high tension releases are obtained at a very short distance from the front.

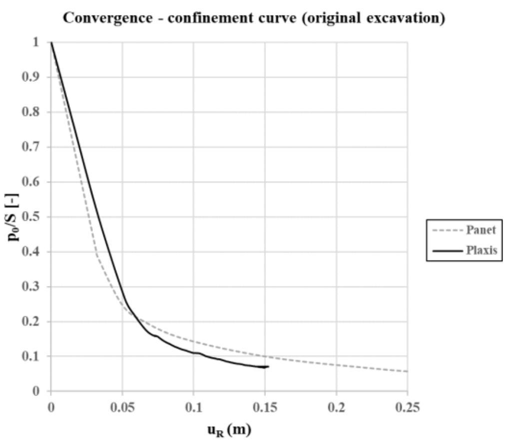

Figure 17 Convergence-confinement curve (original excavation)

From the analysis, axial stresses on the sidewalls are obtained in a range between 250-360 kN/m. For a lining with a thickness of 0.5 m, the resulting internal pressures are of approximately 0.5-0.7 MPa matching the data coming out from in-situ tests.

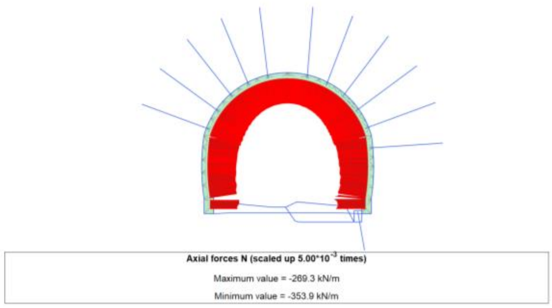

Figure 18 Axial force fitting for the existing lining (As-Built)

Then, the project interventions are modelled according to the intended construction specifications, applying another time the convergence-confinement method to the actual project state. From the analyses for the study of the free cavity, the actual state of the project is modelled at first. Considering the absence of an inverted arch, and therefore the lack of homogeneity in terms of cavity stiffness, the rigidity parameters are calibrated through specific transversal numerical analyses, in order to get the overall behaviour of the tunnel.
The milling process is simulated as a homogeneous enlargement of the section. Figure 19 shows the comparison between actual and project state status for the axisymmetric analyses. The propaedeutic consolidation operations of the milling are calibrated assigning increments of the mechanical properties around the tunnel.

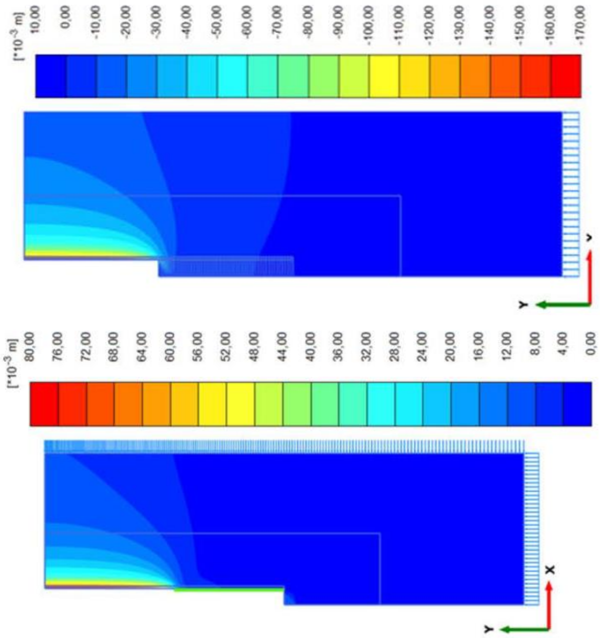

Figure 19 Axisymmetric analyses of the tunnel original excavation (on the top) and with the milling-reinforcement (on the bottom)

Figure 20 shows the 2D analysis for the A1 section. The curves obtained (Figure 21) are coupled in order to evaluate the behavior of the cavity during the milling operations.
After the analysis process, the design is carried out in accordance with the NTC2018 (i.e. Italian construction code).

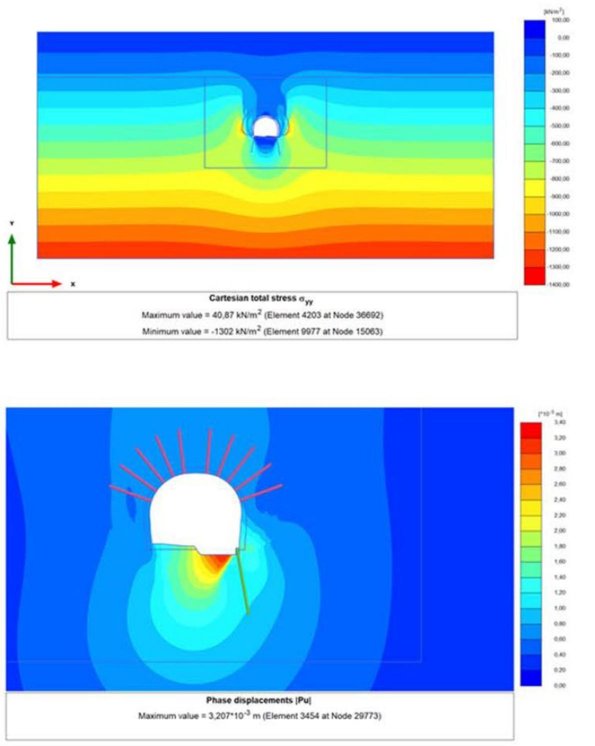

Figure 20 2D FEM analysis with PLAXIS for the design (Section A1)

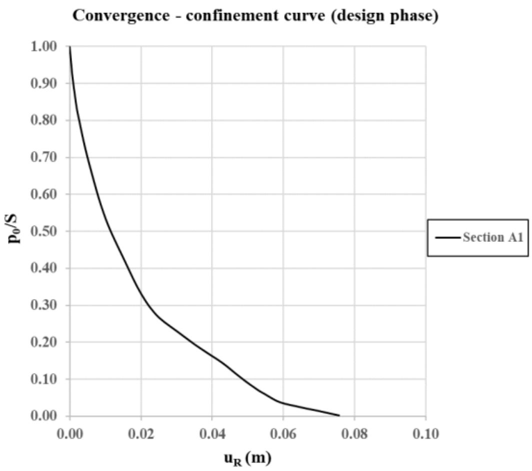

Figure 21 Convergence-confinement curve (design phase, Section A1)

5. BIM INTEGRATED DESIGN

After defining the interventions to be designed and after verifying them by FEM analysis, these are digitalized using a BIM approach. The following objectives are considered:
- Drawing the executive documentation;
- Extracting quantities of materials directly from the federated model;
- Carrying out clash detection operations with respect to the intervention phases.

The project undergoes a new breakdown by intervention typology, obtaining models divided by discipline and assigned to specific technicians, who can work in parallel, using the same references. For each Milestone, technicians can share information in the Federated Model located in the main ACDat, allowing adequate verifications, validations and approval procedures.

5.1 Design phases

The tunnel digitalization is created following a specific workflow capable of guaranteeing an in-depth level of control of all the elements involved and of accelerating the modelling through the development of a parametric library. The phases of the integrated design are as follows (Figure 22):
- Phase 1: development of parametric sections for the components extending in the longitudinal direction of the tunnel (e.g. ballast, lining);
- Phase 2: development of the parametric components for work operations and following the tunnel section (e.g. GFRP);
- Phase 3: integration of the different components and models within the Federated model, in order to allow verification, reporting and approval activities;
- Phase 4: clash Detection activities (Hard and Workflow Clash), Model Checking and time estimation using specific software to check for any project inconsistencies.

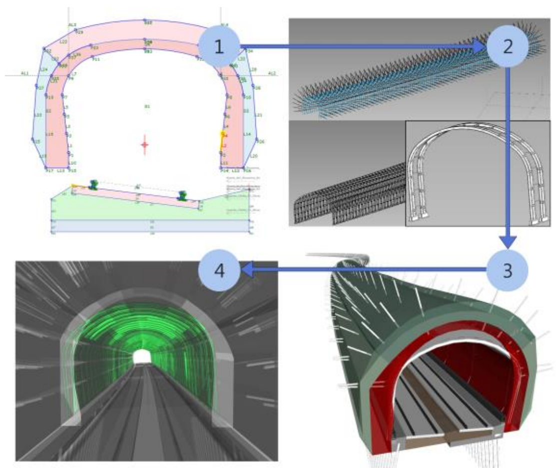

Figure 22 BIM workflow of the design phase

5.2 BIM management

One of the main purposes of BIM is to collect, store, share and manage data. ETS is investing in the implementation of a specific platform, ETS Management System, in a Private Cloud environment.
The system consists of 12 applications divided into three main areas:
- Design & Coordination: with Common Data Environment with browsing/querying system to manage libraries and models;
- Construction: for cost and take-off quantity, analysis of work phases and management of the documentation;
- Management of the information related to the models and on-site monitoring.

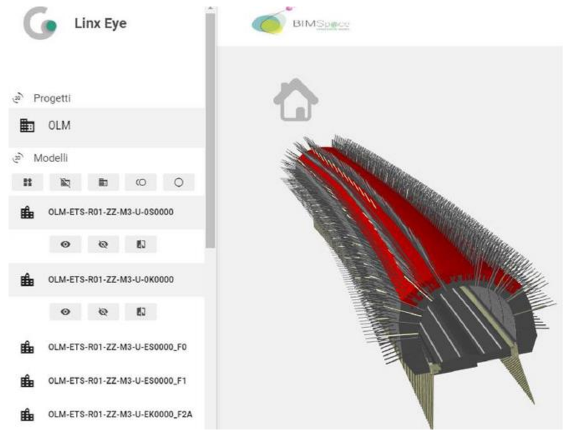

Figure 23 Application of the ETS platform: Link Eye (Design & Coordination) while querying the IFC model of the tunnel

6. CONCLUSIONS

Galleria Olmata presents numerous challenges: during the cognitive phase (surveying with limited stop of the traffic, old tunnel with limited knowledge of the actual state), during the design phase (adjustment and optimization of the clearance, cavity filling, water management), in the planning phase of the works, and, last but not least, the realization.
The integration of the entire process into a BIM environment is not yet an automated step, but it is still considered necessary to extend the potential of BIM to the tunnel infrastructure during planning, design, construction and facility management.

6. SPECIAL THANKS

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