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Geotechnical Challenges and Technical Solutions for Settlements Reduction for the New Access Gallery to the Ceneri base Tunnel (Switzerland)

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Abstract - This paper deals with the main results of an extensive monitoring campaign carried out to quantify the vertical displacement due to the installation of some pre-loads to be realized before the construction of an artificial tunnel. As part of the "Sigirino access tunnel" project, this concrete structure will be realized on highly deformable, saturated silty so that some relevant settlements are expected, therefore they must be minimized to satisfy Serviceability Limit State requirements. Monitoring results are compared with outcomes given by bidimensional finite element analysis, to provide the basis for an appropriate design of the tunnel and to predict the stress-strain response of the structure itself during its work life.

Keywords**:** numerical modeling, FEM, settlement reduction, tunneling, pre-loads.

1. Introduction

The evaluation of settlement and their evolution over time certainly represent an issue of primary importance for Serviceability Limit State verifications of civil engineering structures. While the Ultimate Limit State represents a scenario modeled by introducing unfavorable load combinations and conservative estimation of the material's strength, the Service Limit State introduces assumptions as close as possible to reality. The magnitude of settlements is strictly connected to their functionality, and the definition of appropriate threshold values is related to the structural scopes and usages. According to the 1D consolidation theory, the application of a load over a limited extension foundation lying on a saturated fine-grained soil, results in the occurrence of excess pore water pressure. Therefore, at the end of the loading phase an 'immediate settlement' will occur due to shear strains. According to [1] and [2], the subsequent time-dependent process of pore pressure dissipation and effective stress change causes the "consolidation settlement". The time-dependent phenomenon which describes the evolution of pore pressure and soil deformation is known as consolidation. The "consolidation settlement" is followed by the "secondary settlement" due to the viscous nature of the soil. The total displacement experienced by the soil will result from the sum of the above-mentioned three components, and their relative importance is related to the rate at which loads are applied and by the nature of the soil. Within this framework, the application of pre-loads is one of the most widespread techniques consisting of surcharging the ground with a uniformly distributed surface load before the construction of the intended structure. The purpose is to take up the settlements under the structures before they are built (Fig.1).

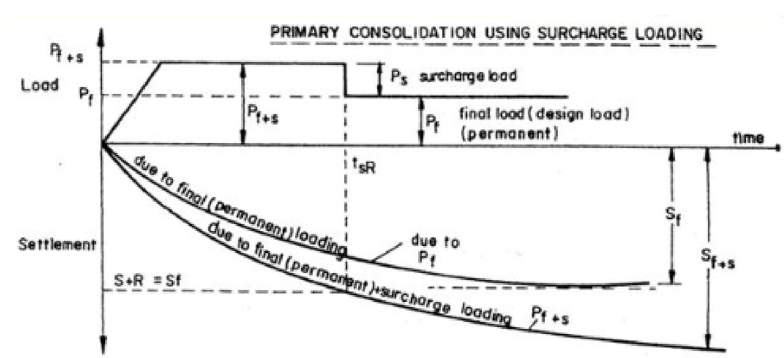


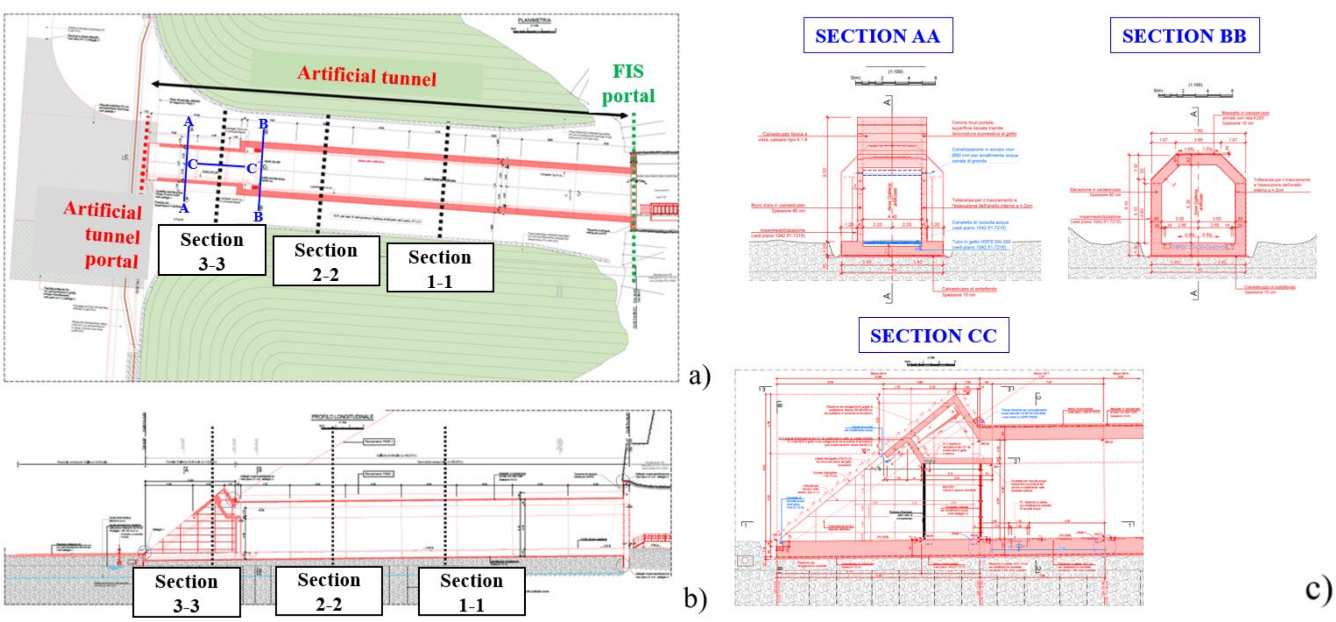
Fig. 1: Primary consolidation using surcharge loading.

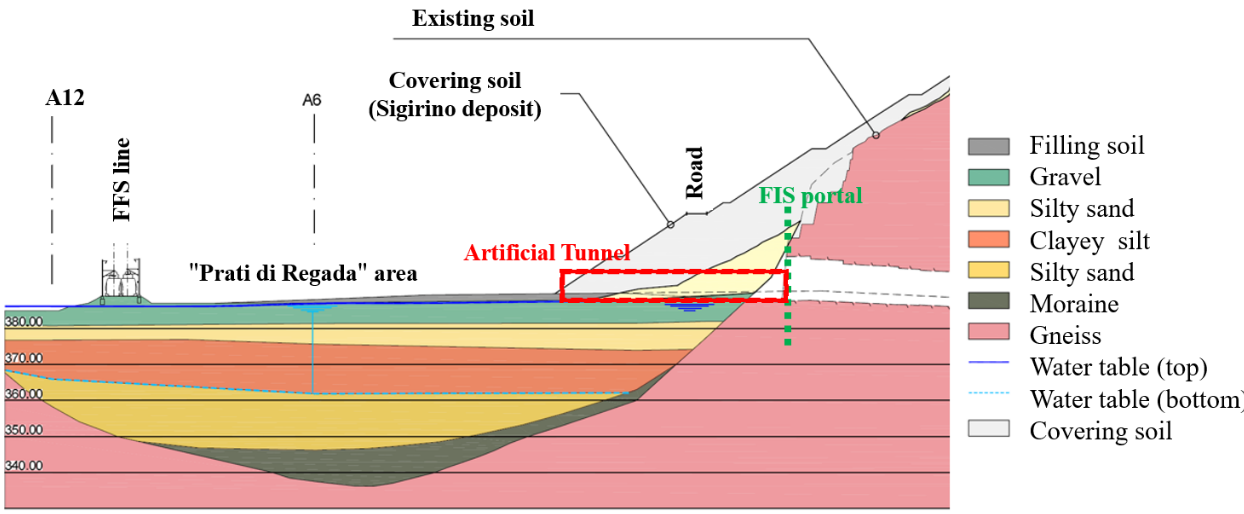
This paper analyses the effectiveness of a pre-loads system aimed at minimizing subsidence below an artificial tunnel to be realized on cohesive, saturated soils. Results obtained by an extensive monitoring system are compared with finite element analyses to evaluate the strain response of the structure during its work life and to design further settlement reduction measures.

2. Design aspects and geotechnical challenges

The new access tunnel (FIS), already excavated as a logistics tunnel, represents the access for the Swiss Federal Railways personnel to perform maintenance operations on the new Ceneri Base Tunnel ([3]-[4]). As part of the "Sigirino access tunnel" project, a new artificial tunnel (Fig.2 a,b) is planned to be realized at the FIS portal to ensure continuity with outside even once the Sigirino deposit - maximum height approx. 28m - will be realized. The new artificial tunnel will be a reinforced concrete structure of approx. 69.0m length with a variable structure: i) the tunnel close to the portal has a rectangular section (height=4.80m, internal width=4.40 m; slab thickness=1.00m, elevation thickness=0.40m, section AA Fig. 1c); ii) the section close to the FIS portal has a hexagonal section (maximum height=6.15m, net width=6.0m, slab thickness=1.0m, elevation thickness=0.80m, section BB Fig.2 c). The new artificial tunnel will be realized close to the toe Sigirino deposit ("Prati di Regada" area). Proceeding from the top to the bottom, the following main geological units can be distinguished: i) "organic soil" approx. 0.5÷1.0 m; ii) "fill": a backfill soil up to 4 m; iii) "gravel": a layer of gravelly sand with many pebbles and a little silt fraction, where is expected the main aquifer, approx. 5÷6 m thick; iv) "silty sand" and "fluvio-lacustrine deposits", approx. 6÷7 m; v) "clayey silt": a layer of clayey silt with fine sand, lacustrine deposits, with a thickness ranging between 9 and 17 m; vi) "deep silty sand": a layer of fine compact silty sand, glacio-lacustrine deposits, thickness between 0 and 15 m; vii) "moraine": a layer of gravelly sand with silt and moraine deposits, with a thickness of 1-2 m; viii) good quality "Gneiss". Finally, a rock outcrop is expected to be close to the connection with FIS portal (Fig.2 d).

This paper presents the main challenges of the "Sigirino access tunnel" project describing the main issues encountered in the design of the new artificial tunnel, together with the key role of the numerical modelling. The main challenges were related to the following: i) realization of a stiff, concrete structure founded on high compressibility, saturated soils; ii) evaluation and minimization of the expected settlements before the construction of the AT; iii) identification of settlements threshold values to guarantee structural safety and serviceability limit state requirements.



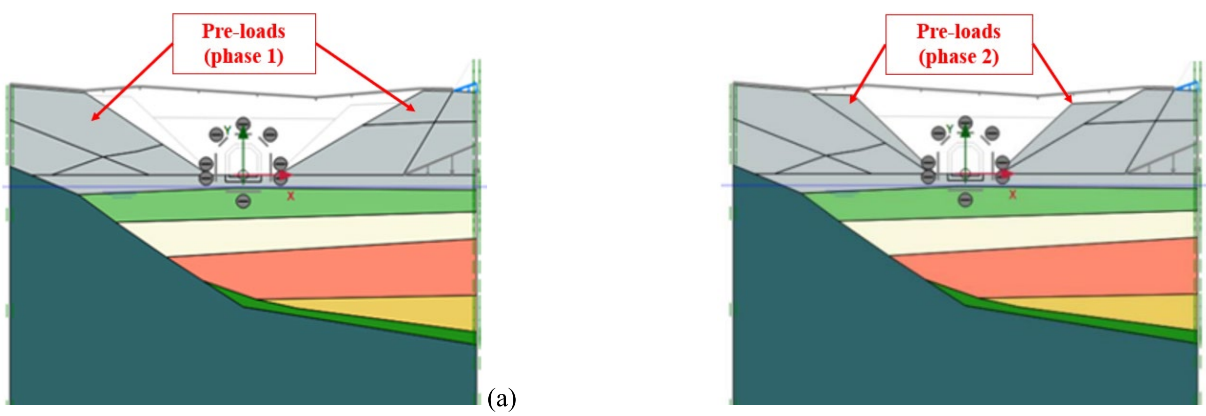


d)

Fig. 2: Artificial tunnel: a) general plan; b) longitudinal profile; c) standard cross-sections; d) geological cross-section along the axis of the artificial tunnel.

3. Technical solutions for settlement reduction solutions and monitoring system

The expected settlements were minimized prior the construction of the new artificial tunnel by the construction of a series of pre-loads consisting of earth-compacted embankments raised step-by-step over time. Therefore, between September 2020 - July 2021 and between April 2023 - June 2023 two series of lateral pre-loads, named respectively "phase 1" and "phase 2", were raised at each side of the area where the AT will be realized (Fig.3).



(a) (b)

Fig. 3: Section 2-2, pre-loads in FE *Plaxis2D* models: a) phase 1; b) phase 2.

The vertical displacements resulting from the application of the lateral pre-loads are automatically measured through a continuous monitoring system consisting of assestimeters (AS). They are placed at three cross sections along the future AT, placed at different distances from the tunnel portal, respectively Section 1-1 (distance +40.58m), Section 2-2 (distance +25.71m) and Section 3-3 (distance +10.86m), as shown in (Fig.4a). Settlements are assessed regarding a "fixed point" far from the new tunnel, while the whole monitoring system is integrated by readings given by inclinometers (INC) and piezometers (F) placed into boreholes at different depths (Fig.4b). Water pressure and displacements measurements are continuously collected and stored on a web platform.

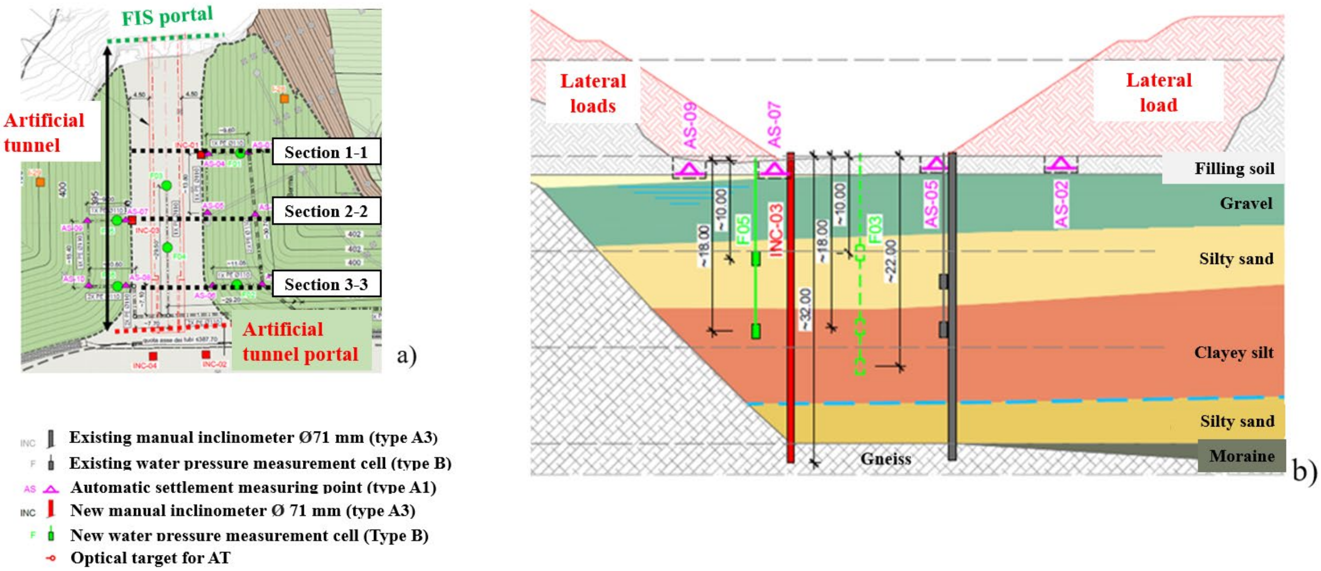


Fig. 4: a) Plan view of the artificial tunnel; b) cross-section 2-2 and instrumentation.

4. Numerical analysis and comparison with monitored data

Bidimensional Finite Element analyses were carried out to simulate the pre-loads installation and to compare monitored settlements with numerical results, thus allowing to predict the stress-strain response of the new tunnel during the design phase. FE analyses are carried out at section 1-1, section 2-2, and section 3-3 under drained conditions because of the installation of vertical drains in the area under consideration to prevent static liquefaction occurrence of fine soils when monotonically loaded ([5]). The FE analyses were carried out by the code *Plaxis2D*, Vers. 21.01.00.479 ([6]) under plane deformation conditions. The model was constrained by hinges on the lower edge and rollers on the vertical edges. The soil was discretized by 10'000 triangular meshes that were densified in the most relevant clusters. A Hardening-Soil and Mohr-Coulomb constitutive law are adopted for soil and rock units, respectively. The application of lateral pre-loads is simulated by progressively applying appropriate overloads at different steps, so a "gravity loading analysis" is performed as the initial phase, while a "plastic calculation" mode is carried out for the subsequent phases. Geotechnical parameters adopted for soils and rock units are summarized in Table 1.

Table 1: Geotechnical properties.

Properties	Filling soil	Gravel	Silty sand	Clayey silt	Silty sand	Moraine	Gneiss
Cohesion, c'(kPa)	0.1	0.1	0.1	0.1	0.1	5.0	1000
Friction angle, Ø (°)	37.0	38.0	33.0	20.0	35.0	38.0	40.0
Unit volume Weight, γ (kN/m^3)	22.0	20.0	19.0	19.0	20.0	20.0	27.0
Coeff. of earth pressure at rest, k_0 (-)*	0.39	0.38	0.45	0.65	0.42	0.38	0.7
Elastic modulus, E_{50}^{ref} (MPa)	100.0	75.0	35.0	5.0	35.0	78.0	5000
Oed. elastic modulus, E_{oed}^{ref} (MPa)	100.0	75.0	35.0	5.0	35.0	78.0	-
Unl. - Rel. elastic modulus, E_{ur}^{ref} (MPa)	200.0	150.0	70.0	20.0	70.0	170.0	-
Power, m (-)	0.20	0.50	0.60	0.60	0.50	0.30	-
Poisson ratio, ν (-)	0.20	0.27	0.32	0.33	0.30	0.27	0.20
Hydraulic conductivity, k (m/day)	$0.1\cdot10^{-3}$	$1\cdot10^{-3}$	$0.01\cdot10^{-3}$	10^{-8}-10^{-9}	$1\cdot10^{-6}$	$1\cdot10^{-6}$	-

*Gneiss: k_0 assessed by in situ tests. Soils: k_0 evaluated by 1-sen(φ) correlation under the assumption of normal-consolidation.

The evolution of the measured displacement over time shows a relevant settlement rate developed during the pre-load application phase n.1 followed by a tendency towards an overall stabilization. The application of pre-load phase n.2 induced an increase in the settlement rate still ongoing until now (Fig.5a).

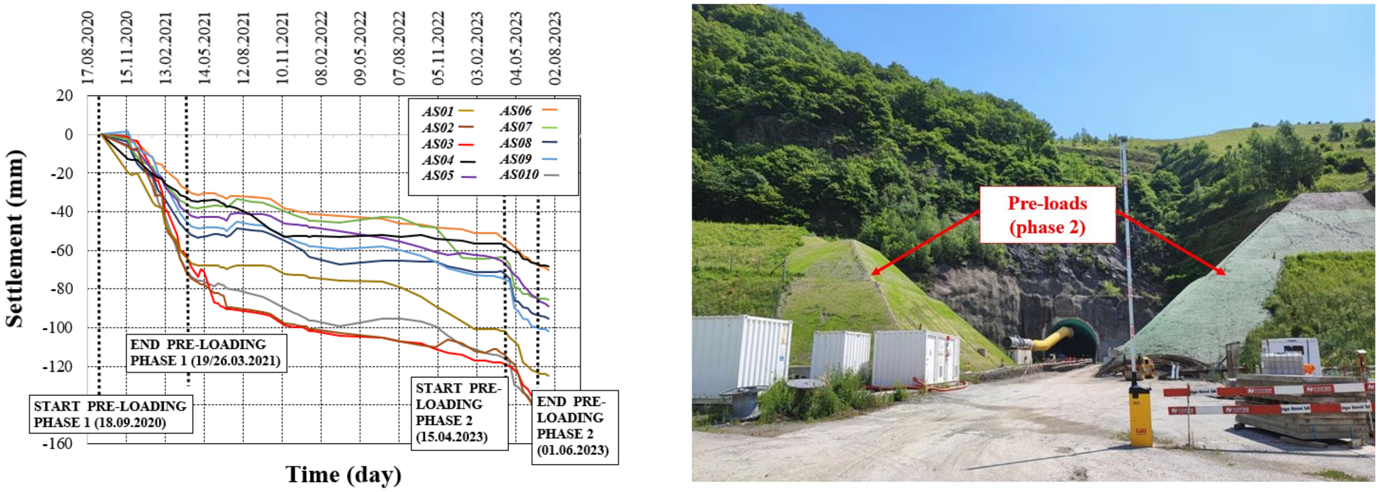
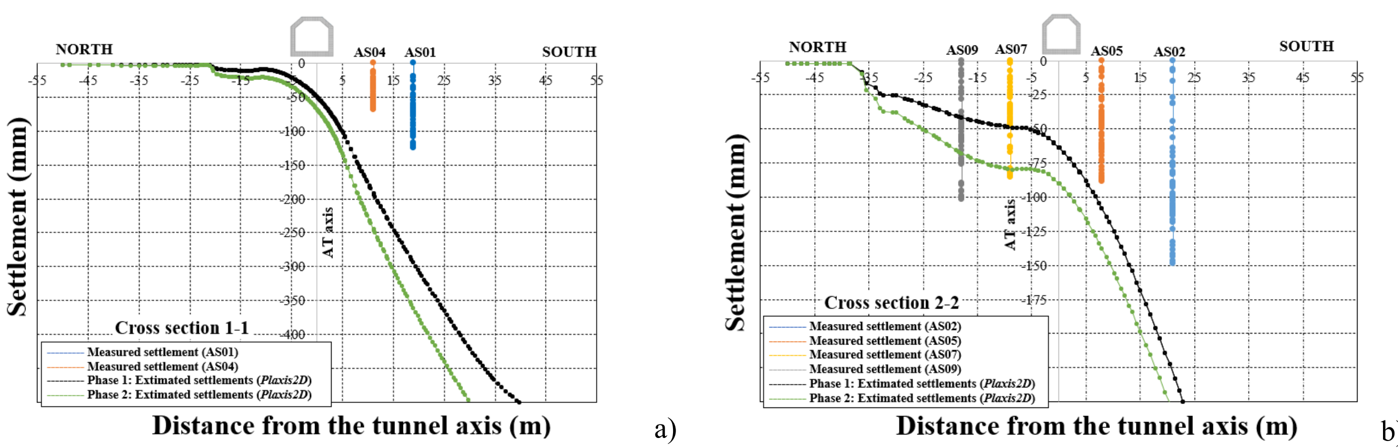
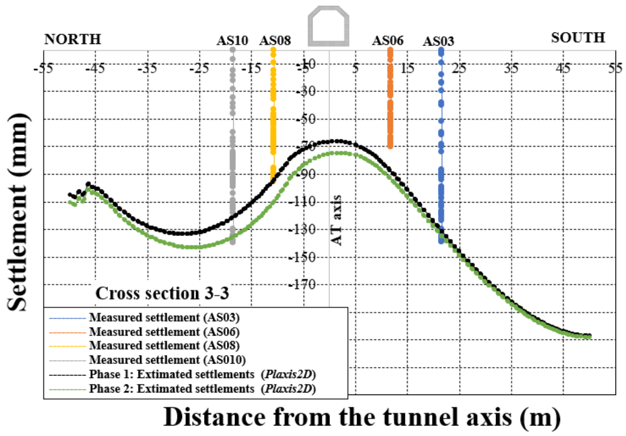


Fig. 5: a) Evolution of settlements over time the time by AS01-AS10 measurements; b) Lateral pre-loads, phase 2.

A comparison between the measured settlements along cross sections 1-1, 2-2, 3-3 (coloured lines) and those provided by FE models is proposed in Fig.6a-b-c. The black and green lines represent settlement values given by the finite element analyses at the end of pre-load 1 and pre-load 2, respectively. In general terms, measurements and estimated settlement well correspond for cross sections 2-2 and 3-3. Conversely, the instrumental measurements provided by the AS04 and AS01 (section 1-1) are lower than *Plaxis2D* predictions. The reason for this difference is that numerical analyses are carried out under 2D conditions, so 3D effects are not taken into account by the FE model. Indeed, cross-section 1-1 is the closest to the FIS portal and the rock outcropping, the latter - due to its high stiffness - influences the settlement distribution of the neighboring sections. This is a purely three-dimensional effect, and it is not considered in the modeling of cross-section 1-1 in which the presence of close stiffer layers cannot be captured. On the other side, cross-sections 2-2 and 3-3 are characterized by more homogeneous geology in the longitudinal direction, therefore the three-dimensional effects are not so relevant, so monitored data are in good accordance with numerical results. Finally, it can be observed that - both from measurement data and numerical results - the South-side settlements are systematically greater than those along the North-side ones: this is due to the immersion of the rock in the transversal direction. Moreover, the benefits due to pre-load phase 2 can be observed also in terms of the predicted settlement because of the difference between black and green lines.





c)

Fig. 6: Comparison between predicted settlement after pre-load phase 1 (black dotted line) and pre-load phase 2 (green dotted line) with measured settlements: a) cross section 1-1; b) cross section 2-2; c) cross section 3-3.

The measures of the settlement under the tunnel axis of the new artificial tunnel are given in Fig.7 regarding the cross-sections 1-1, 2-2, and 3-3 (blue/orange/grey line). An interpolation between monitored data and numerical results allowed to estimate the evolution of the settlement along the longitudinal direction. Higher settlement values approx. 70/80mm can be observed close to the AT portal (section 3-3) and in the middle of the tunnel (section 2-2) where the compressible soils reach their maximum thickness below the AT foundation, while settlements tend to reduce moving toward section 1-1. The overall settlement along the longitudinal direction can be assumed almost constant for the three monitored sections, with a certain supposed decrease moving to the FIS portal because of the presence of the rock outcrop.

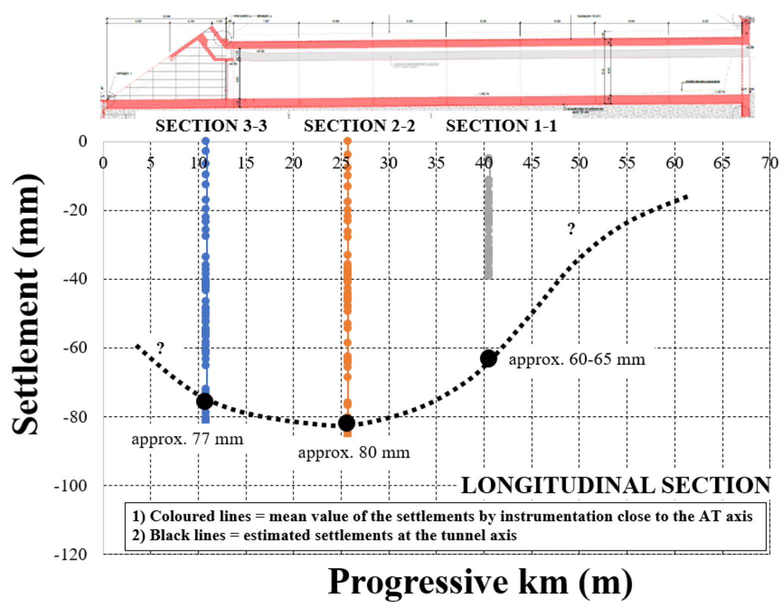


Fig. 7: Longitudinal section of the tunnel axis: monitored settlements of cross sections 1-1, 2-2, 3-3 (coloured vertical lines) and estimation of the settlement distribution along the longitudinal direction (dotted black line).

5. Status of the work

The execution of the pre-load phase 1 started in September 2020 and ended after six months, while the placement of pre-load phase 2 started in April 2023 and it is currently concluded. The construction phase of the artificial tunnel started in June 2023 and currently it is on track with the contractual Construction Programme. Since now the reinforced concrete slab is realized, while walls are under construction (Fig.7). Further pre-loads (phase 3) are foreseen to be realized step-by-step along the longitudinal direction during the building of the tunnel which completion is scheduled for December 2023. Finally, the Sigirino deposit will be realized by October 2024.


a)

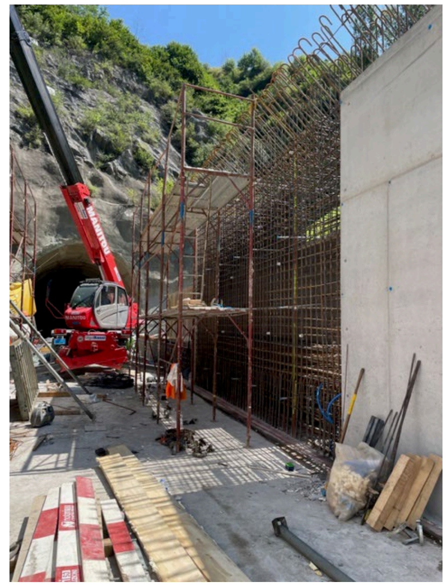

b)

Fig 7: a) Steel reinforced slab construction; b) view of the steel reinforcement placement into the wall of the artificial gallery.

6. Conclusions

Geotechnical challenges and technical solutions adopted to minimize the settlements induced by the construction of an artificial tunnel on highly deformable, saturated cohesive soils are described in this paper. Some lateral pre-loads consisting of earth-compacted embankments were raised over time on both sides of the area where the artificial tunnel will be realized. Settlements are measured and compared with those obtained by 2D finite element analysis, thus highlighting the importance of numerical modeling as a predictive tool for design purposes.

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