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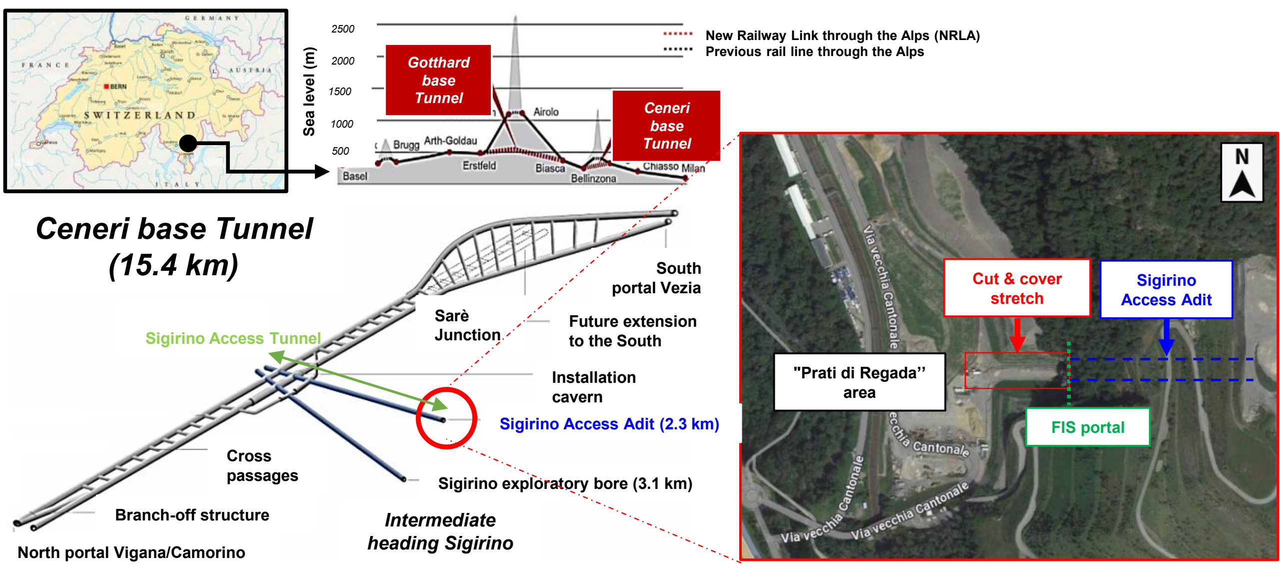
Sigirino Access Tunnel (CBT)

Geotechnical and Design Challenges

This paper focuses on the Sigirino Access Tunnel, which provides regular maintenance access to the Ceneri Base Tunnel. Focusing on the cut&cover section of the tunnel, the main design, geotechnical risks, and challenges encountered during the project and construction are described. The measures taken to minimize settlements and the main results of an extensive monitoring campaign are given.

1. Introduction and Main Challenges of the Project

The Ceneri Base Tunnel (CBT) is the southern part of the New Railway Link through the Alps (NRLA), crossing the Swiss Alps from North to South. The NRLA is designed to create a continuous flat-rail connection from Basel to Milan, aimed at reducing travel times, increasing the efficiency and sustainability of freight traffic, and connecting Switzerland to the European high-speed railway network. Within this frame, the CBT is a new 15.4 km long tunnel connecting the Swiss cities of Lugano and Bellinzona (Figure 1). It consists of a north portal (Vigana), the main section with the intermediate heading (Sigirino), a south portal (Vezia). It is made of a twin-tube system with a single-track railway tunnel linked through cross-passages spaced 325 m. The excavation of the main tunnels started in 2010 from the intermediate heading of Sigirino, and the infrastructure was opened to traffic in 2020. The Sigirino Access Tunnel represents the access for the Swiss Federal Railways personnel to carry out maintenance operations on the CBT ([1]). The Sigirino Access Tunnel consists of two stretches: the Sigirino Access Adit and a Cut&Cover Tunnel (CCT), the latter to allow continuity with the outside even once the Sigirino deposit is completed (Figure 1). Connected to the Sigirino Access Adit, the CCT is partially realized on deformable, saturated cohesive soils and partially built on good-quality rock mass. This paper presents the main geotechnical challenges associated with the design and construction phase of the new "Sigirino Access Tunnel", together with monitoring results. The main challenges of the project mainly consist of: 1) realization of a concrete structure based on deformable soils in saturated conditions where differential settlements are expected; 2) estimation of the settlements before the construction of the CCT; 3) identification of technical solutions to minimize the expected settlements below the CCT and below the existing railway line in operation to guarantee structural safety and serviceability limit-state requirements.



1 The layout of NRLA project and view of the new Sigirino Access Tunnel (CBT).

Zugangsstollen Sigirino (Ceneri Basistunnel)

Geotechnische und konstruktive Herausforderungen

Dieses Paper erläutert die wichtigsten konstruktiven Herausforderungen bei der Ausführung des in offener Bauweise konstruierten Sigirino-Zufahrtstunnels sowie die dabei angewandten technischen Lösungen. Dabei werden die Massnahmen vorgestellt, die ergriffen wurden, um Setzungen zu minimieren, ebenso wie die Ergebnisse einer Überwachungskampagne sowie ein Vergleich zwischen den erwarteten und tatsächlich aufgetretenen Setzungen. Die Gesamtkosten des Vorhabens belaufen sich auf 21 Mio. CHF und werden vollständig von der Schweizer Bundesbahn (SBB-CFF-FFS) getragen. Die Arbeiten begannen im Mai 2022 und endeten im Dezember 2024 erfolgreich mit der Inbetriebnahme des Tunnels.

Galeries d'accès Sigirino (tunnel de base du Ceneri)

Défis géotechniques et conceptuels

Ce document présente les principaux défis en matière de conception et les solutions techniques adoptées pour la construction en tranchée couverte du tunnel d'accès Sigirino. Il inclut une présentation des mesures prises pour minimiser les tassements, des résultats de la campagne de surveillance et une comparaison entre les tassements prévus et réels. Les frais de construction totaux du projet s'élèvent à CHF 21 millions et sont entièrement pris en charge par les Chemins de Fer Fédéraux Suisses (SBB-CFF-FFS). Les travaux ont démarré en mai 2022 et ont été achevés avec succès en décembre 2024.

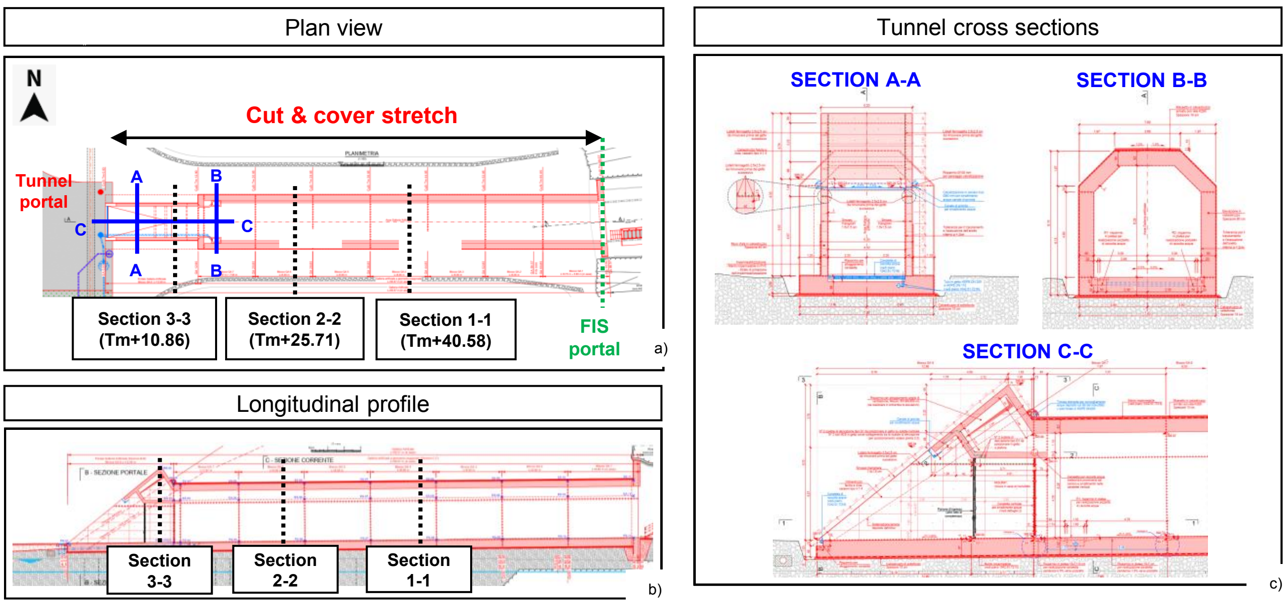
Cunicolo di accesso di Sigirino (GbC)

Sfide geotecniche e progettuali

L'articolo presenta le principali sfide progettuali e le soluzioni tecniche adottate nella costruzione del tunnel cut&cover del cunicolo di accesso di Sigirino. Si espongono inoltre le misure volte a minimizzare i cedimenti delle opere coinvolte, i risultati di una campagna di monitoraggio e un confronto tra i cedimenti previsti e quelli effettivi. Il costo complessivo dell'opera ammonta a 21 milioni di franchi, interamente finanziato dalle Ferrovie Federali Svizzere (SBB-CFF-FFS). I lavori sono iniziati a maggio 2022 e sono stati completati con successo a dicembre 2024.

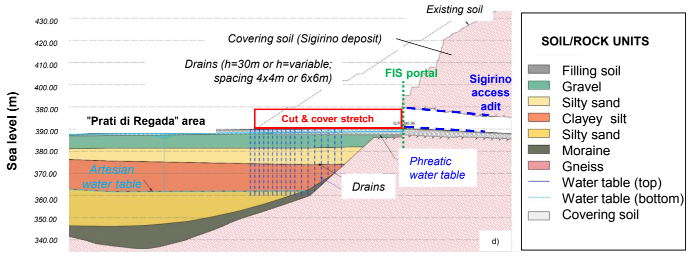
2. Cut&Cover Tunnel and Geotechnical Characterization

The cut&cover stretch of the Sigirino Access Tunnel is a 68.00 m long reinforced concrete structure made of hexagonal section (maximum height = 6.15 m, net width = 6.00 m, slab thickness = 1.00 m, elevation thickness = 0.80 m), and rectangular sections close to the portal (height = 4.80 m, internal width = 4.40 m; slab thickness = 1.00 m, elevation thickness = 0.40 m, Figure 2 a,b,c). Based on a proper number of boreholes and proceeding from the top to the bottom, the cut&cover stretch lies on a shallow layer of "organic soil", "filling soil", "gravel" where the main aquifer is expected, "silty sand" and "fluvio-lacustrine deposits", "clayey silt" with fine sand and lacustrine deposits, "deep silty sand" of fine compact silty sand and glacio-lacustrine deposits, "moraine" made of

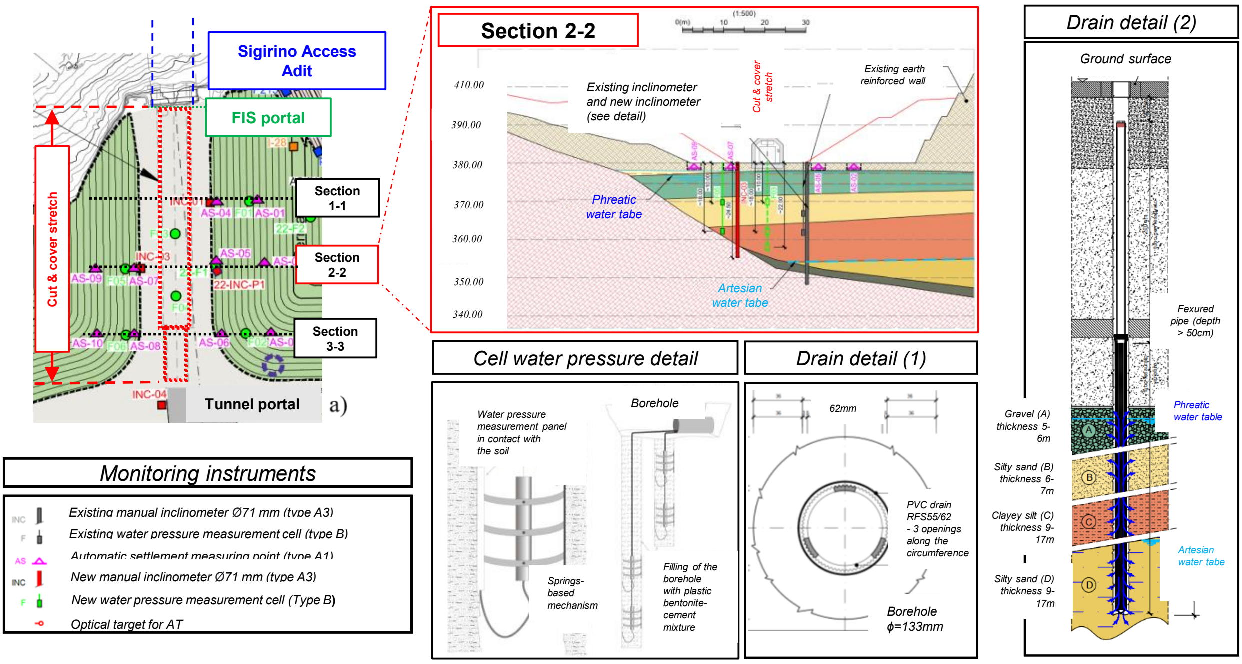


2 Sigirino Access Tunnel, cut&cover section: a) general plan, b) longitudinal profile, c) standard cross-sections.

gravelly sand with silt and moraine deposits, "gneiss". A rock outcrop is identified close to the FIS portal (Figure 2d). Then, an extensive in-situ test (Flat Dilatometer, Cone Penetration Tests), as well as laboratory test (Compression/Extension Triaxial Test, Direct Simple Shear Tests, Oedometer Tests) allowed the estimation of the hydraulic conductivity, shear strength, deformability properties and consolidation coefficients of the geological units revealing a certain anisotropy ([2, 3]). An upper water table was identified at 386.00 m.a.s.l, while a lower water surface was expected at 360.00 m.a.s.l so that all the soil units were expected to be in saturated/unsaturated conditions. The saturation state, poor deformability properties of the soils, non-homogenous layering along the longitudinal direction, and the filling loads to be realized above the CCT led to identifying the static liquefaction and differential settlement occurrence as the main issues during the construction and operational life of the cut&cover stretch of the Sigirino Access Tunnel.



2 d) Geological cross-section and soil/rock units along the axis.



3 Plan view of the monitoring system and details.

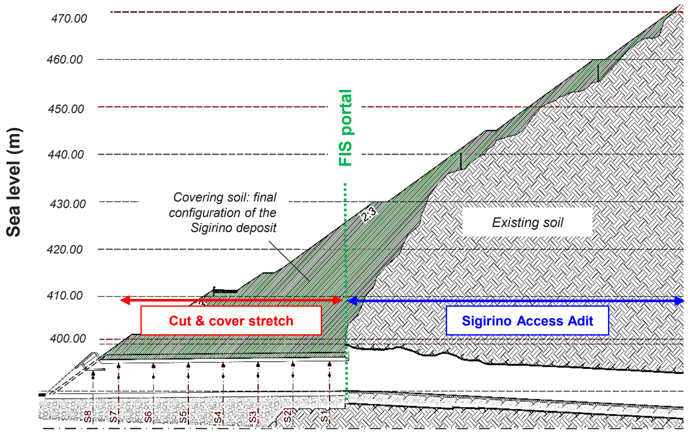
3. Monitoring System

An extensive monitoring system has been implemented to evaluate settlements and excess pore water pressure with depth before and during the CCT construction (Figure 3). Vertical displacements were automatically measured by the installation of a continuous monitoring system consisting of assestimeters placed below the CCT slab at three cross sections at different distances from the tunnel portal, respectively Section 1–1 (distance Tm+40.58), Section 2–2 (distance Tm+25.71), and Section 3–3 (distance Tm+10.86).

Parameter/option	Option n.1	Option n.2	Option n.3
Cost saving	1.0	2.5	3.0
Environmental impact	1.0	2.0	2.0
Safety	1.0	1.0	3.0
Feasibility	1.0	2.0	3.0
Durability/Maintenance	1.0	2.0	2.0
Total score	1.0	1.9	2.6

***Table 1** Multicriteria comparison between the intervention measures (1.0: 'good'–> 3.0: 'poor').*

Settlements were assessed regarding a "fixed point" based on rock and far from the Sigirino access gallery. The system was integrated by periodical optical targets installed inside the CCT, continuous automatic measurements given by piezometers, inclinometers, and cell water pressures placed into boreholes at different depths.



4 Final configuration of the Sigirino deposit.

4. Technical Solutions for Excess Pore Pressure and Settlement Reduction

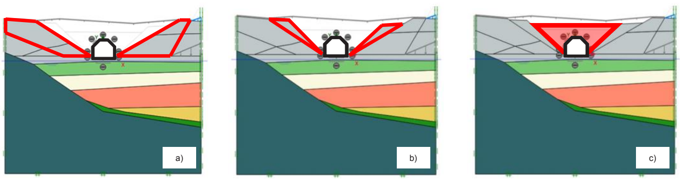
Approximately 1300 vertical PVC drains Øexternal = 65 mm, Øinternal = 55 mm, spacing: 3.0 x 3.0 m / 4.0 x 4.0 m / 6.0 x 6.0 m or 8.0 x 8.0 m, depth: 23–60 m were installed ([3]). They allowed excess pore pressure dissipation during the construction phase, or in case of extreme rainfall, thus preventing bearing capacity reduction due to temporary shear strength loss or excessive settlements, the latter representing a key aspect for Serviceability Limit State checks of structures ([4]). Some measures were analyzed and compared to minimize the settlements below the CCT. The first option consisted of 'pre-lateral loads': the ground would be loaded with a uniformly distributed load consisting of earth-compacted embankments raised step-by-step over time before and during the CCT construction. The construction of deep foundations ('drilled piles' below the foundation slab) until reaching the rock mass bedrock has been considered as option n. 2. Finally, the injection of cement grout at high pressure in the soil after vertical drilling ('jet grouting') was the third option. The above solutions have been compared and weighted in terms of costs, environmental impact, safety level, feasibility, and durability (Table 1). The first option was recognized as the best technical solution since it provided the best score for all the analyzed criteria. The adopted loading sequence mainly consisted of five phases (Table 2) until reaching the final configuration (Figure 4).

Phase n.	from	to	Description	Figure
1	September, 2020	March, 2021	Execution of the lateral pre-loads both at the North and South sides of the artificial gallery to be realized.	5a
2	April, 2023	June, 2023	Execution of the lateral pre-loads both at the North and South sides of the artificial gallery to be realized.	5b
3	September, 2023	October, 2023	Cut&Cover Tunnel construction. Execution of the lateral pre-loads at the North/South side (from Tm+0.00 to Tm+44.00), until reaching +402.00 m.a.s.l.	5c
4	January, 2024	February, 2024	Execution of the lateral pre-loads at the North/South side, and above the Cut&Cover Tunnel segments already realized (from Tm+44.00 to Tm+68.00), until reaching +402.00 m.a.s.l.	5c
5	February, 2024	October, 2024	Completion of the final deposit	–

***Table 2** Loading phases.*

5. Numerical Analysis

The analyses were performed by using the code Plaxis2D (Version 21.01.00.479), and the bi-dimensional model was constrained by rollers on the vertical edges and hinges on the lower edge. Finite Element analyses (FE) were carried out under plane strain conditions at different relevant sections from the tunnel portal. Drained conditions were assumed because of the presence of vertical drains. The soil was discretized then by triangular meshes, while Mohr-Coulomb or Hardening-Soil constitutive law were adopted for rock units and soil, respectively (Table 3). The installation of lateral preloads was simulated by applying overloads at different steps (Figure 5).



5 Pre-load phases at section 2–2. Red polygons represent the pre-loads near and above the Sigirino artificial tunnel: a) phase n.1; b) phase n.2; c) phase n.3 and phase n.4–5.

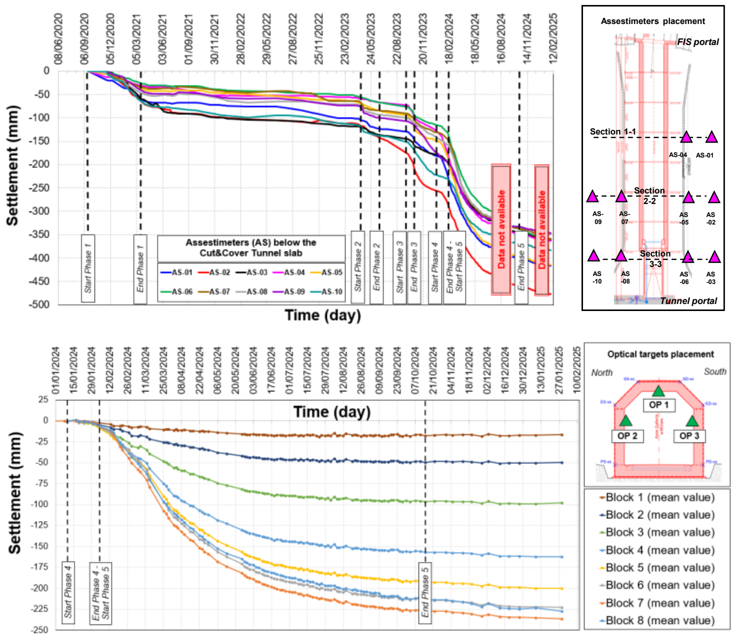
6. Results and Status of the Work

Displacement over time – measured by assestimeters installed under the CCT slab and by optical targets installed inside the CCT – highlights a relevant settlement developed during each loading phase, i.e. 'immediate settlements' and 'consolidation

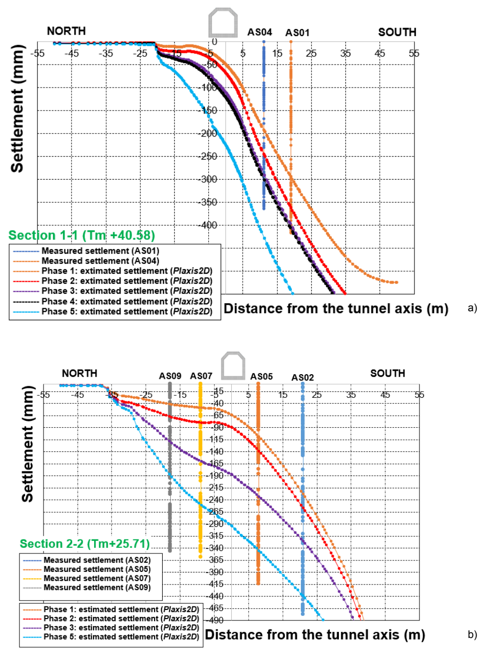
Properties	Filling soil	Gravel	Silty sand	Clayey silt	Silty sand	Moraine	Gneiss
Cohesion, c'(kPa)	0.1	0.1	0.1	0.1	0.1	5.0	1000
Friction angle, φ (°)	37	38	33	20	35	38	40
Unit volume weight, γ (kN/m^3)	22	20	19	19	20	20	27
Coeff. of earth pressure at rest, k_0(NC) (-)	0.39	0.38	0.45	0.65	0.42	0.38	0.7
Elastic modulus, E_{50}^{ref} (MPa)	100	75	35	5	35	78	5000
Oed. elastic modulus, E_{oed}^{ref} (MPa)	100	75	35	5	35	78	–
Unloading-reloading elastic modulus, E_{ur}^{ref} (MPa)	200	150	70	20	70	170	–
Power, m (-)	0.20	0.50	0.60	0.60	0.50	0.30	–
Reference pressure, p_{ref} (kPa)	100	100	100	100	100	100	–
Failure ratio, Rf (-)	0.9	0.9	0.9	0.9	0.9	0.9	–
Min. mean effective stress, p_{lim} (kPa)	10	10	10	10	10	10	–
Poisson ratio, υ (-)	0.20	0.27	0.32	0.33	0.30	0.27	0.20
Hydraulic conductivity, k (m/day)	10^{-4}	10^{-3}	10^{-5}	10^{-8}–10^{-9}	10^{-6}	10^{-6}	–

***Table 3** Geotechnical properties of the soil/rock units.*

settlements' (Figure 6 a, b). When no loads are applied, i.e. between phase n-1 and phase -n, it follows a certain stabilization where displacement due to viscosity under constant effective stress ('secondary settlements'). A comparison between the estimated settlement provided by the FE analyses models and the measured ones at cross section 1–1 and section 2–2 is given (Figure 7a, b). The curved lines represent settlements obtained by the FE analyses at the end of each phase. A certain accordance between

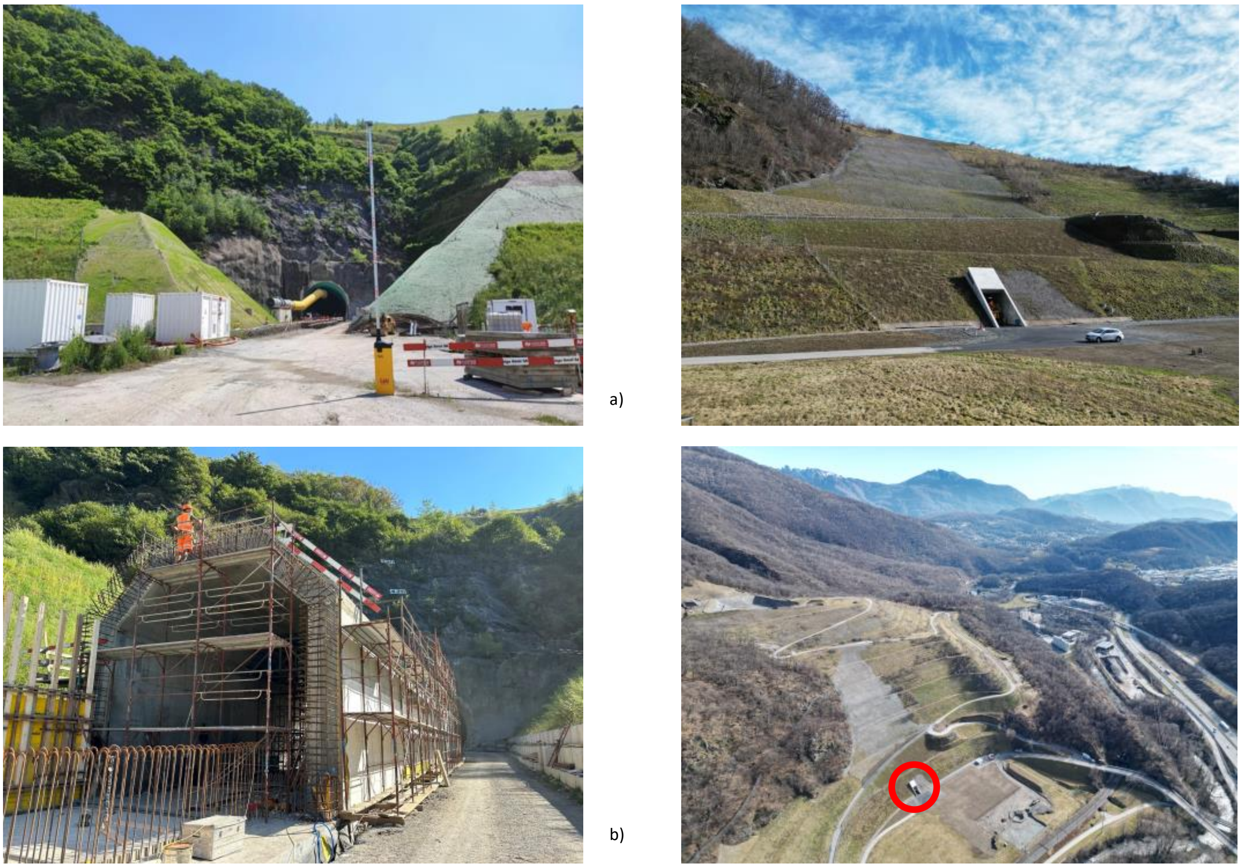


6 a/b) Measured settlements over time: assestimeters (AS01–AS10) and periodical optical target readings (OT01–OT08) inside the Cut&Cover Tunnel.



7 a/b) Comparison between measured settlements and predicted settlements at each loading phase: cross section 1–1 and cross section 2–2.

estimated and measured settlements can be appreciated, especially for Section 1–1. A possible reason for the scatter between measured and estimated data in Section 2–2 could be addressed by considering the influence of 3D effects. FE calculations are performed as bidimensional analyses, therefore 3D effects due to load conditions and geological heterogeneity, are expected not to be considered. The maximum settlement values detected since the construction of the CCT are approximately 25 cm. In terms of absolute settlements, the actual settlements were about 20% higher than those estimated by the calculation; conversely, in terms of differential settlements, the actual settlements were lower than those predicted by the calculation model. The contract was tendered by Ferrovie Federali Svizzere for 16 Mio CHF. All works started in September 2020 with successfully commissioned in October 2024 (Figure 8).



a) c) b) d)

***8** a) Pre-load phase n.2; b) construction of the artificial tunnel portal; c) final configuration; d) aerial view.*

7. Conclusion

This paper presents the main geotechnical challenges associated with the construction of the Sigirino access tunnel. Since the structure is realized on fine-grained, saturated soil layers where differential settlements are expected, technical solutions were adopted to avoid the occurrence of static liquefaction and to minimize vertical displacement. An efficient drainage system was realized, and pre-loads were installed before and during the tunnel's staged construction. Measuring data are compared with numerical results, thus confirming the importance of the observational method.

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PROJECT KEY DATA

Region
Canton Ticino

Client
Swiss Federal Railways (SBB-CFF-FFS)

Design, site supervision and overall construction management
- Design consultancy services: Pini Group SA
- Site supervision: Project Partners Ltd Consulting Engineers

Contractor for the Civil Works
Joint Venture "Consorzio FFS Sigirino" composed by: Ugo Bassi SA, Impresa Luigi Notari (Suisse) SA, Rofer SA, Ecorecycling SA

Key data

Construction period:	2022–2024
Start of operations:	2025
Construction costs of civil works:	CHF 12 Mio
Total construction cost:	CHF 21 Mio
Length:	Total length: 2.3 km, of which 70 m for the cut&cover tunnel
Cut&Cover tunnel Cross section:	approx. 57 m²

Special features
Cut&Cover tunnel, soil-structure interaction, settlements