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3D modelling of a complex soil-structure interaction between a new motorway artificial tunnel and an existing underground hydraulic channel

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Abstract

Three-dimensional (3D) numerical modelling is an essential tool for analyzing complex geotechnical problems involving soil-structure interaction. In this study, a 3D numerical model was developed to assess the design and construction of a new artificial tunnel required for the upgrade of an existing motorway. The proposed tunnel crosses above an old underground hydraulic channel used to divert a river, creating a critical interaction between the new and existing infrastructure. The model incorporates detailed geotechnical and structural characteristics, as well as the sequential construction and operational phases. Special attention was given to reproducing the construction process realistically to evaluate its effects on the surrounding ground and structures. The results of the analysis enabled the identification of optimal technological solutions to ensure the stability of the new artificial tunnel and to safeguard the structural integrity of the underlying hydraulic channel.

Keywords: Artificial tunnel; 3D modelling; Soil-structure interaction; Structural integrity

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1. Introduction

The design of geotechnical structures invariably requires the formulation of a model of the soil-structure system, a representative framework essential for reproducing and analyzing its physical and mechanical behavior. A model represents an appropriate simplification of reality, and the skill in modelling lies in determining the level of simplification that allows distinguishing between relevant and negligible features (Wood, 2017).
These principles become particularly critical in more challenging geotechnical contexts, where soil-structure interaction plays a decisive role. In such situations, traditional empirical or limit-equilibrium approaches often prove inadequate, as they are applicable only under simplified geometric, loading, and boundary conditions. Consequently, numerical modelling becomes an indispensable tool for achieving a more realistic representation of the system's behaviour. In particular, significant spatial variability in system geometry, applied loads, or boundary conditions requires three-dimensional numerical modeling to accurately capture the overall stress-strain response and to identify and mitigate local criticalities in the engineering solution. In this context, three-dimensional numerical analyses provide substantial support in the study and design of shallow, mixed (Wang et al., 2019), and deep foundations (Jenck et al., 2009; Bagheri et al., 2019), particularly when the loading and geometric conditions of the foundation preclude the use of simpler approaches for assessing soil-structure interaction. Moreover, three-dimensional numerical modelling is widely employed to investigate the interaction between tunnels and surface structures or infrastructures (Barla et al., 2012; Fargnoli et al., 2015; Yuan et al., 2019; Barla et al., 2021), as well as the interaction between infrastructures and landslides (Bru et al., 2018; Vassallo et al., 2019; Barla et al., 2024).
This article presents a study of the interaction between the new Torbella artificial tunnel, part of the upgrading project for the A7-A10-A12 motorway system of Genova, the Gronda project, and the existing hydraulic channel located beneath the footprint of the planned structure (Fig. 1). The limited depth of the channel, combined with the geometric configuration of the proposed structure, constrained by the alignment of the existing highway, required the design of an articulated mixed foundation system (shallow foundations and piles) to prevent detrimental overloading of the existing hydraulic channel compromising its stability. Three-dimensional numerical modelling was employed to assess the effectiveness of the designed foundation system in limiting the interaction with the underlying channel, as well as to identify and mitigate local criticalities in order to preserve the structural integrity of the channel, which plays a significant role in ensuring the stability of the planned structure.

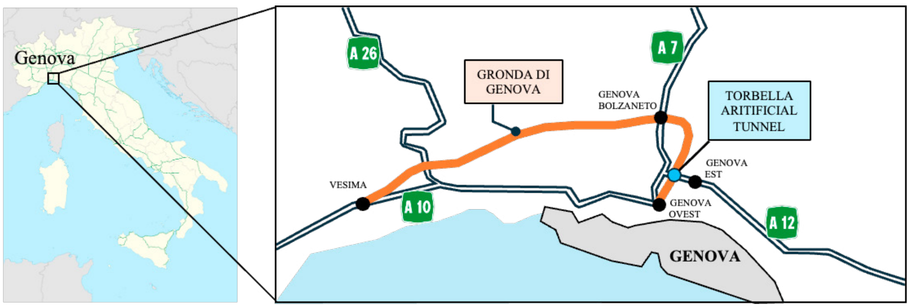

Fig. 1. Siting of the Torbella artificial tunnel within the infrastructural framework defined by the Gronda project.

2. The new Torbella artificial tunnel

The Torbella artificial tunnel, included within the final design for the upgrading of the A7-A10-A12 motorway system of Genova (Gronda project), has been conceived to encase and protect the existing A12 motorway, enabling the construction of a platform that will serve as a strategic staging area for the development of the new A7 bypass route, through the construction of a new viaduct and a new natural tunnel.
As shown in Fig. 2(a), the Torbella artificial tunnel intersects an existing hydraulic channel, which is positioned diagonally beneath the motorway alignments of the A12 motorway axis. The buried hydraulic channel was built in the second half of the 1960s as an underpass hydraulic structure for the Torbella creek to allow for the construction of the A12 motorway platform. The channel was constructed by open-cut excavation down to the foundation level, followed by casting of the foundations and base slab, erection of the concrete lining (walls and vault), and subsequent backfilling. The depth of the hydraulic channel relative to the foundation level of the artificial tunnel is

limited to only a few meters. In particular, at the point where the two axes intersect, the depth decreases to approximately 3.4 m, as shown in Fig. 2(b). This critical condition may jeopardise the structural integrity of the hydraulic channel due to the increased loading imposed by the Torbella artificial tunnel.

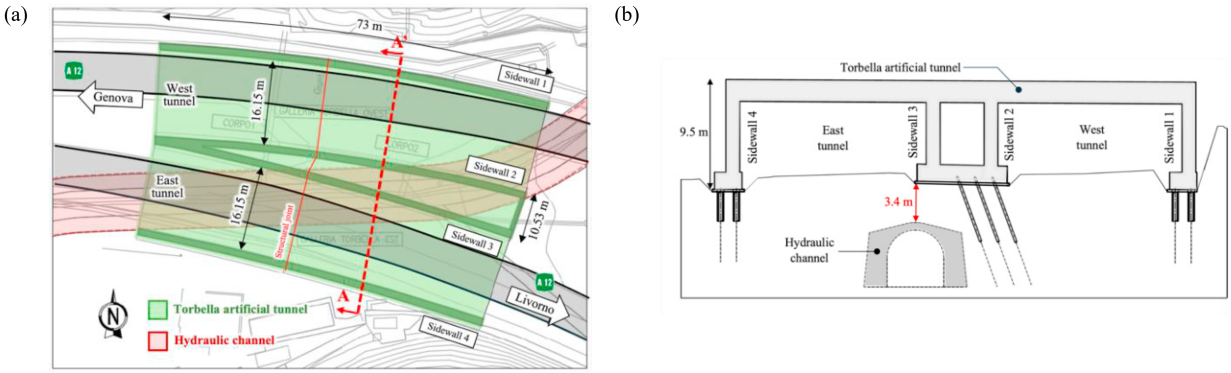

Fig. 2. (a) Plan view of the designed Torbella artificial tunnel and the intersection with the hydraulic channel. (b) A-A' cross-section of the Torbella artificial tunnel.

To mitigate the overloading of the channel, the foundation layout of the Torbella artificial tunnel has been designed to prevent direct interaction with the underlying structure by adopting pile and mixed foundation systems as illustrated in Fig. 3a. Specifically, sidewall 1 is founded on Ø600 mm piles, 16 m in length, spaced 1.40 m apart, connected by a foundation beam 1.50 m thick and 2.40 m wide; sidewall 4 is founded on Ø600 mm piles, 18 m in length, with the same 1.40 m spacing and a foundation beam 1.50 m thick and 2.40 m wide. The two central walls (2 and 3) are founded on a footing slab with a variable width ranging from 2.92 m to 10.53 m and a thickness of 1.5 m. The structure features a transversal joint at approximately 28 m along the East tube and 31.4 m along the West tube. This divide creates two structurally independent units, both statically and seismically, which will be referred to as body 1 (easternmost) and body 2 (westernmost) (Fig. 2a). The central slab transfers the loads of Body 1 to Ø600 mm piles with a length of 18 m. For Body 2, interference with the Torbella channel necessitated the use of Ø300 mm micropiles, 20 m in length and inclined at 20° in order to prevent any interaction with the underlying channel. Furthermore, in the zone of intersection between the central foundation slab axis and the hydraulic channel axis, characterized by a limited embedment depth and the presence of a shallow connection shaft for minor streams (Fig. 3a and Fig. 3b), the foundation system transitions to a direct foundation. As shown in Fig. 3b the hydraulic channel in the area of interest has a constant cross-section, with a crown height of 5.65 m measured from the foundation level and a maximum width slightly exceeding 9 m. The unreinforced concrete lining, characterized by a variable thickness, reaches a maximum value of 2.02 m at the base of the sidewall and a minimum thickness of 65 cm at the crown.

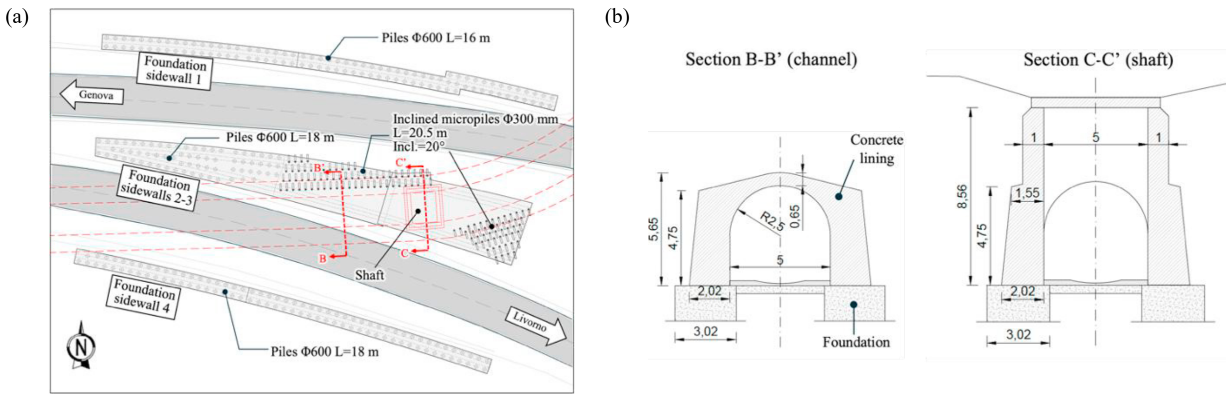

Fig. 3. (a) Plan view of the foundation layout of the Torbella artificial tunnel; (b) Cross-section of the channel (section B-B') and of the shaft (section C-C').

3. Study of the soil-structure interaction

This section presents the three-dimensional numerical model developed to assess the effects of the construction of the new Torbella artificial tunnel on the existing underlying hydraulic channel. The 3D model, implemented using the finite-difference software FLAC3D 7.0 (ITASCA, 2019), was employed to identify the portions of the channel most affected by the artificial tunnel construction, verifying the preservation of its structural integrity.

3.1. The 3D numerical model

The 3D model, extending 168 m in the E-W direction and approximately 135 m in the N-S direction, was sized to fully include the area where the hydraulic channel underpasses the A12 Motorway and interacts with the planned artificial tunnel, while avoiding boundary effects in the numerical solution. The model incorporates the current site topography, reconstructed from detailed surveys, the A12 motorway alignment, and the complete geometry of the hydraulic channel and the shaft, derived from as-built documents and field investigations. The geological-geotechnical framework was reconstructed by spatially interpolating the two-dimensional cross-sections available in the design documentation, themselves based on extensive borehole data. From bottom to top, the subsurface consists of the Ronco Formation bedrock (ROC), its weathered mantle (ROC-Cap), the overlying alluvial deposits (Croc), and the fill materials associated with the A12 construction. An elasto-plastic constitutive law with Mohr-Coulomb failure criterion was adopted for all geotechnical units. The strength and deformability parameters of the geotechnical units used in the numerical analysis are summarized in Table 1.

Table 1. Deformability and strength parameters of the geotechnical units.

Geotecnical units	γ [kN/m^3]	E [MPa]	ν [-]	ϕ' [kPa]	c' [kPa]
Filling soils	20	25	0.3	30	0
Alluvial deposit (Croc)	20	25	0.3	27	10
Altered bedrock (ROC-Cap)	24	150	0.25	22	30
Bedrock (ROC)	25	1500	0.20	38	75

For the structural elements of the existing hydraulic channel (bottom slab, foundations, and lining), the characteristic strength and deformability parameters of the concrete were derived from the average compressive strength obtained on cylindrical specimens retrieved through micro-coring. These elements were modelled assuming an elasto-plastic constitutive law with Mohr-Coulomb failure criterion. Conversely, the reinforced-concrete foundation beams and the central slab of the Torbella artificial tunnel were modelled as linear-elastic elements, assuming a C30/37 concrete class as specified in the design. The strength and deformability parameters adopted for all structural components are reported in Table 2.

Table 2. Deformability and strength parameters of the structural elements.

Structural element	γ [kN/m^3]	E [MPa]	ν [-]	f_{ck} [MPa]	ϕ' [kPa]	c' [MPa]	σ_t [MPa]
Lining, bottom slab and foundations of the hydraulic channel	24	30000	0.2	19.8	37	4.9	2.2
Foundation beams and central slab of the Torbella artificial tunnel	25	33000	0.2	-	-	-	-

The structural elements of the hydraulic channel and the shallow foundations of the Torbella artificial tunnel were modeled as volume elements, while the Ø600 bored piles and micropiles were represented with “pile-type” elements, assuming soil-side failure. Without load tests, the ultimate pile-soil shear resistance was estimated from the geotechnical unit strength parameters. The tunnel superstructure was explicitly modelled using “shell-type” elements for the sidewalls and cover. The 3D model also reproduces the site topography, with the valley axis at roughly 110 m a.s.l., hosting the A12 motorway and the hydraulic channel. Boundary conditions included zero-displacement normal to the lateral and bottom faces, and hinge supports at the four lower vertices. Interstitial pressure was considered via the effective stress principle, and the groundwater table, averaging 8 m below ground, was interpolated from geological sections. Fig. 4 summarizes the main construction phases reproduced in the 3D model. Each phase groups all the computational stages required to represent a configuration of interest of the model, each reproducing a key step in the historical and design evolution of the site.

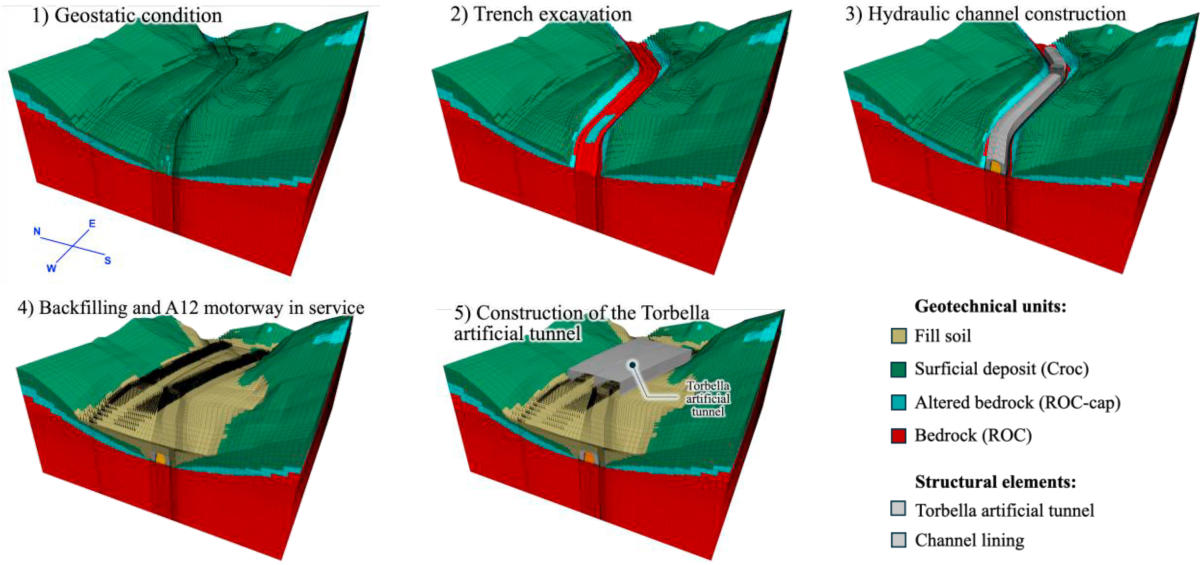

Fig. 4. Main construction phases reproduced in the 3D numerical model.

Phase 1 involves the initialization of the stress state of the model. Starting from the initial geometry of the area, characterized by the presence of the stream incision where the Torbella creek originally flowed, and in the absence of both the A12 motorway alignment and the hydraulic channel, the stress state was assigned by bringing the system to equilibrium under gravitational loads only and by applying a lateral earth pressure coefficient at rest, $k_0 = 1.0$. This stage provides the initial configuration of the valley and defines the baseline stress state for all subsequent computations. Building upon this initial condition, Phase 2 reproduces the excavation of the trench down to the foundation level of the hydraulic channel, approximately 4-5 m below the ground surface and at the bedrock interface, as documented in the as-built drawings. Phase 3 then simulates the sequential construction of the foundations, the bottom slab, and the lining of the hydraulic channel, including the shaft, thereby reconstructing the channel in its original configuration. Once the channel is completed, Phase 4 introduces soil backfilling up to the final elevation of the A12 motorway. The corresponding highway load, applied along the axes of both traffic directions, as prescribed by the Italian Building Code, is subsequently imposed. This stage represents the current stress-strain condition of the hydraulic channel prior to the construction of the planned artificial tunnel. Finally, Phase 5 reproduces the design configuration by simulating the successive construction of the cast in place foundations system and the superstructure of the Torbella artificial tunnel. Initially, only the self-weight of the tunnel is considered, as the structure has not yet developed sufficient stiffness. The model then incorporates the stiffness provided by the fully cured tunnel superstructure and applies at the foundation level the total actions due to the tunnel's self-weight and the accidental loads associated with service conditions, as evaluated through a dedicated structural model. Fig. 5a shows a detailed view of the foundations and the superstructure of the Torbella artificial tunnel, as well as its intersection with the underlying hydraulic channel, while Fig. 5b presents a detailed view of the computational mesh of the channel and the shaft, whose cover lies only 1 m below the bearing base of the central foundation slab of the artificial tunnel. Moreover, as specified in the design documents, a 0.5 m thick rigid cement-treated subbase was included in the model beneath the terminal portion of the central foundation slab.

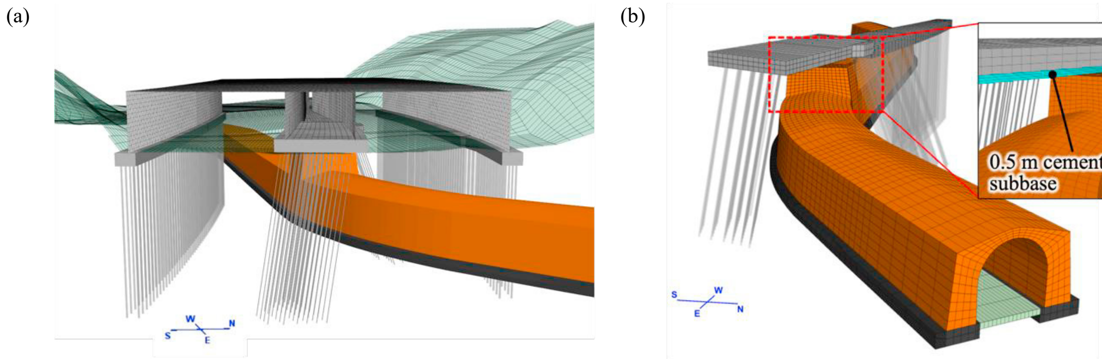

Fig. 5. (a) Detailed view of the foundations and the superstructure of the Torbella artificial tunnel; (b) detailed view of the computational mesh of the channel and the shaft.

3.2. 3D model as a design and verification tool

In the following, some of the results obtained from the proposed 3D model are presented. The model enabled a detailed study of the interaction described above, allowing the identification of design improvements to ensure the stability of the new tunnel and to safeguard the structural integrity of the underlying hydraulic channel. Fig. 6a shows, for phase 5 (completion of the artificial tunnel), the vertical displacements at the central foundation of the artificial tunnel and its interaction with the hydraulic channel. Fig. 6b, instead, presents a detailed plan view of the vertical displacements induced in the hydraulic channel and its deformed configuration resulting from the interaction (magnification factor = 2500).

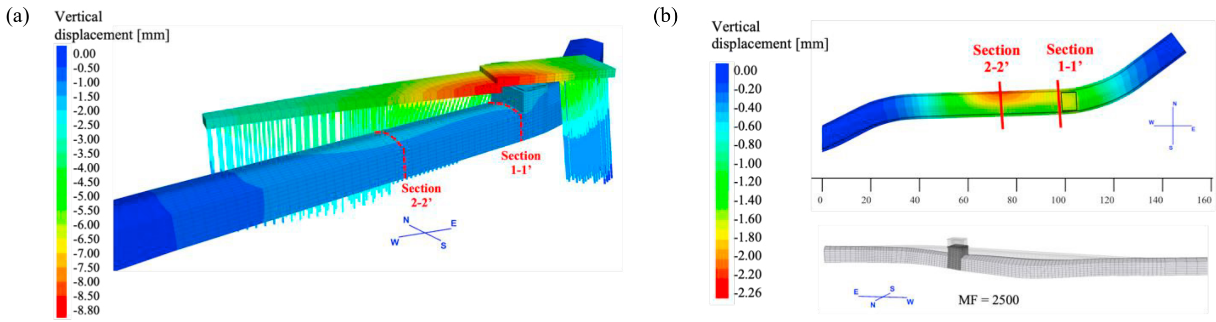

Fig. 6. (a) Vertical displacements of the central foundation slab of the Torbella artificial tunnel and interaction with the hydraulic channel (stage 5); (b) Plan view of the vertical displacements of the hydraulic channel due to the interaction with the artificial tunnel (stage 5).

The construction of the artificial tunnel affects approximately 100 m of the hydraulic channel, particularly in the area intersecting the central foundation of the tunnel. The maximum vertical displacements of the artificial tunnel, about 9 mm, occur in the central portion of the foundation slab where no piles are present, and are fully consistent with the values predicted by the structural model developed for the static and seismic verifications. The vertical displacements induced in the channel, while remaining below 3 mm, exhibit a differential behavior. The analysis also allowed the identification of two transversal sections that may be critical for the stability of the channel lining (Fig. 6): Section 1-1', located at the connection between the lining and the shaft, and Section 2-2', corresponding to the channel portion strongly influenced by the nearby Ø600 bored piles. In Section 1-1', the adjacent shaft, characterized by a very stiff behaviour and with its top located only 1 m below the base of the central foundation, tends to absorb a significant portion of the loads transmitted by the artificial tunnel's direct foundation, transferring them to the closest portions of the channel lining. This condition results in high shear stresses concentrated in the right sidewall lining, potentially compromising the structural integrity of the underlying hydraulic channel. To address this issue and preserve the structural integrity of the channel lining, two design options were compared. The objective was to structurally isolate the shaft by reducing the load it attracts from the artificial tunnel, enhancing the “bridging effect” provided by the micropiles. This was achieved by replacing the rigid cement-treated subbase around the shaft (Design option 1) with compacted backfill material and by increasing the number of micropiles in the adjacent areas (Design option 2), as illustrated in Fig. 7.

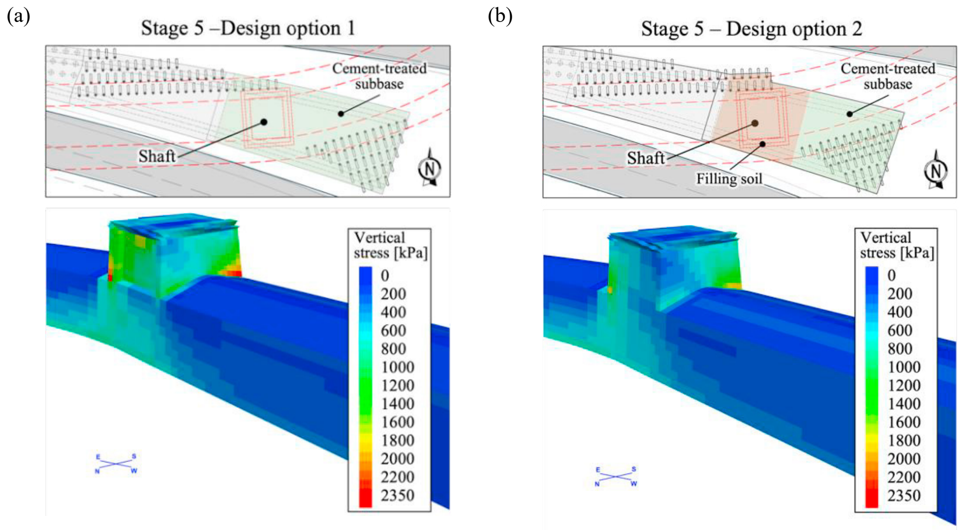

Fig. 7. (a) Initial design of the end portion of the central foundation of the artificial tunnel and resulting vertical stress state in the shaft and channel lining. (b) Final design of the same foundation portion and corresponding vertical stress state in the shaft and channel lining.

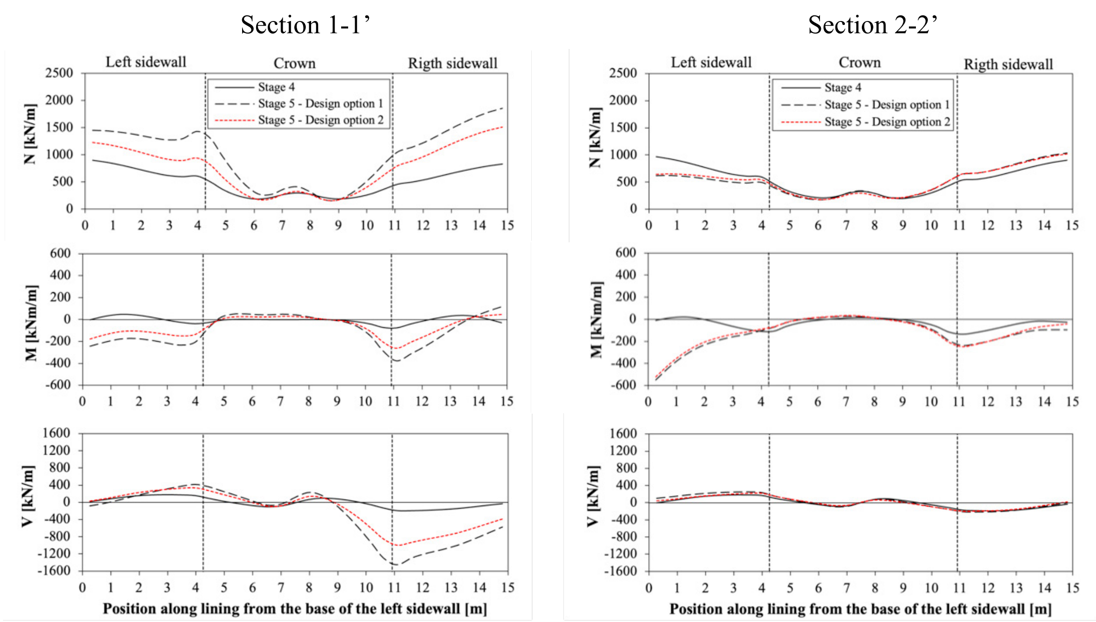

Fig. 8. Normal force (N), bending moment (M), and shear force (V) in Sections 1-1’ and 2-2’ of the channel lining at calculation stages 4 and 5.

This design local improvement was effectively achieved thanks to the ability of the 3D model to reproduce a realistic soil structure interaction. Fig. 8a also reports the distribution of normal force (N), bending moment (M), and shear force (V) for phase 4 (before the construction of the artificial tunnel) and 5 (completion of the artificial tunnel), where a reduction in the internal forces in Section 1-1’ can be observed following the Design option 2

(Phase 5 - Design option 2). This configuration ensures the stability of the new artificial tunnel and to safeguard the structural integrity of the underlying hydraulic channel.
Figure 8 also shows, as for section 1-1', the stress distribution for calculation Stages 4 and 5 for section 2-2'. With reference to section 2-2', the interaction with the adjacent Ø600 piles causes a downward dragging effect on the lining at the left sidewall, inducing differential settlement of the channel in that area. Despite the differential settlement of the lining (Fig. 6b) and the resulting increase in bending moment at the base of the left sidewall (Fig. 8), the lining thickness at the base, slightly over 2 m, ensures the structural integrity of the underlying hydraulic channel.

Conclusions

In challenging geotechnical contexts, characterized by significant spatial variability in system geometry, applied loads, or boundary conditions, soil-structure interaction plays a primary role. In such cases, the design of geotechnical structures requires detailed 3D numerical modelling to accurately capture the overall stress-strain response and to optimise the engineering solution.
In the case study presented in this paper, which examines the interaction between the new Torbella artificial tunnel and the underlying hydraulic channel, the use of a 3D model made it possible not only to accurately assess the extent of the interaction between the two structures, but also to identify the sections of the channel most affected by the artificial tunnel-induced loading. It further enabled a straightforward definition of the design improvement aimed at preserving the structural integrity of the channel while ensuring the stability of the new artificial tunnel.
In such complex contexts, the use of 3D models for soil-structure interaction assessment remains preferable to the adoption of simpler two-dimensional models, as it allows the actual stiffness of the engineering system to be represented and ensures an adequate evaluation of its stress-strain response during the design phase.

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