# Introduction

Tunnels are critical engineering structures designed to overcome natural barriers like mountains and maritime channels, enabling efficient transportation of people and resources. In urban areas, they optimize space by supporting subway systems and essential infrastructure services such as water, sewage, gas, and electrical networks. Their role extends to specialized applications in hydroelectric plants, underground labs, radioactive waste storage, mining, and petrochemical industries. As a key technology, tunnels address complex geotechnical and structural challenges, contributing significantly to national infrastructure and development.

The structural design and analysis of tunnels require consideration of numerous geotechnical parameters and the accurate estimation of several critical factors such as tunnel convergence (or closure), the pressure in tunnel lining, and plastification of the surrounding rock mass. For shallow tunnels, surface settlement also becomes a significant concern. The stress and deformation fields that develop around a tunnel are influenced by the tunnel’s depth, the tunnel wall geometry, anisotropy of in situ stresses, presence of water, and surface structures in the case of shallow tunnels. Additionally, the excavation method and lining installation play crucial roles, as does the rheological behavior and coupling of both the rock mass and the lining.

A key challenge in tunnel modeling is capturing the interaction between short-term and long-term structural behavior. The time-dependent behavior can greatly impact deformations and the overall stability of the tunnel. Short-term response such as rock mass plasticization, tunnel wall closure, and loading on the lining may develop not only during tunnel construction but also progressively over months or even years.

In adjacent tunnels such the twin tunnels, there is also the interaction due to the proximity of the tunnels, lagging distance between escavation faces and, if present, transverse galleries, which cause localized stress distribution and overloading the main tunnels. Furthermore, unlike single tunnels, twin tunnels with gallery can only be studied with three-dimensional models.

Most investigations on adjacent or twin tunnels focus on shallow tunnels (e.g., [1, 2 , 3, 4, 5] to cite a few recent ones). Ground settlement and interaction with surface structures are typical concerns for urban metro systems. Since the present study is only interested in deformation fields at gallery’s influence zone considering nonlinear and time-dependent constitutive models, for simplicity, only deep twin tunnel domain is consdered. A comprehensive review on ground settlements involving twin tunnels can be found in [6]. For deep twin tunnels, some recent investigations are presented below.

Regarding to analytical formulations, Chen et al. [7] developed a solution using complex variables, Fourier transformation, and the alternating Schwarz method, considering rock mass and lining in elasticity. Their findings show that the interaction between adjacent tunnels vanishes when the spacing exceeds six times the tunnel radius and the lining significantly reduces the stress concentration, especially at high lateral stress coefficients.

Ma et al. [8] proposed an analytical method, verified by a numerical solution using FLAC3D software for determining the plastic zones around deep circular twin tunnels without linings, restricting themselves where there is no overlap between the two plastic zones. In this case, the authors adopted the elastoplastic perfectly constitutive model for the homogeneous and isotropic rock mass, with the Mohr-Coulomb criterion. Also carried out parametric studies to understand the influence of the distance between the twin tunnels, cohesion, the angle of internal friction, and the vertical and horizontal initial stresses acting on the shape and depth of the plastic zones. These authors stated that the plastic zone around the tunnel provides a relevant theoretical basis for defining and designing the support. In that respect, an excessive plastic zone would significantly affect the stability and functionality of a tunnel. Reducing the extension of the plastic zone around tunnels is, therefore, of significant importance in engineering tunnel design projects.

Guo et al. [9] develop an elastic analytical solution for the stress field around twin circular tunnels under hydrostatic pressure using the complex variable and the superposition principle. They found that tangencial stress in tunnel wall increased as the distance between the parallel tunnels decreased and the supporting pressure leads to the radial stress increasing and the tangential stress decreasing.

According to Fortsakis [10], in a realistic construction context, twin tunnels are excavated and supported with a delay, so that the second tunnel is usually built after the first one has advanced enough to maintain a longitudinal separation distance between the faces. Trought numerical model, considering a perfect elastoplastic rock mass with Mohr-Coulomb criterion and a linear elastic lining, he concluded that the advance of the subsequent tunnel mobilizes the redistribution of stresses and deformations in the zone between the tunnels, resulting in additional loading of the preceding tunnel.

Chortis and Kavvadas [11] carried out parametric 3D finite element analyses to verify the interaction between deep twin tunnel, with circular and non-circular cross-section, supported by a shotcrete elastic linear lining. Was considering the rock mass with linear elastic behavior and perfectly plastic, with Mohr-Coulumb failure criteria. The study investigates the axial forces that develop in the primary lining of the twin tunnels as a function of the main geometric and geomaterial parameters, but without considering the potential time-dependent deformations (creep effect) that occur in some types of rock masses.

In another study but same constitutive models, Chortis and Kavvadas [12] examined the axial forces acting on the primary support in the perpendicular intersection zone between two deep tunnels. The results of the analysis indicated that the zone of influence extends approximately two diameters from the main tunnel to each side from the center of the intersection and that the interaction effects are practically eliminated when they exceed this influence zone. During the construction of the transverse tunnel, the surrounding rock mass is subjected to a redistribution of stresses, causing an additional load on the main tunnel, precisely in the intersection zone. If these additional loads exceed the load capacity of the primary support of the main tunnel, a potentially unstable region can develop, leading to failure, especially in adverse geotechnical conditions.

Using parametric three-dimensional numerical analyses, Chortis and Kavvadas [13, 14] investigated the effect of building a transverse tunnel that intersected deep twin tunnels perpendicularly, focusing the study on the axial forces and the circumferential and longitudinal bending moments acting on the primary support of the intersection regions, respectively. The constitutive model of the rock mass was a perfect elastoplastic following the Generalised Hoek-Brown failure criterion while the shotcrete a linear elastic material. According to the authors, the critical zone in the primary support of the main tunnel extends approximately one diameter from the main tunnel, on both sides of the centre of the intersection.

In this context, the main contributions of this paper may be summarized at both the material and tunnel analysis levels. At the material level, the constitutive state equations of the rock mass are formulated within the framework of coupled plasticity-viscoplasticity, which is relevant for clayey rocks. Such a framework allows capturing the irreversible instantaneous tunnel response (plasticity) as well as the delayed irreversible response (viscoplasticity). As regards the mechanical behavior of concrete material defining the lining, which is classically modeled through linear elastic relationships, the present analysis considers an aging viscoelastic rheological model relying upon the Bažant and Prasannan Solidification theory [15, 16]. At the structure analysis level, the simulation of deformation in the highly interacting material system components (namely, rock mass and lining), resulting from the excavation process of twin tunnels and transverse gallery, is handled using finite element simulations performed in a three-dimensional setting. From the computational viewpoint, the excavation process and lining placement are simulated by means of the activation/deactivation technique. The constitutive models formulated for the rock mass and lining constituent as well as the related numerical integration schemes are implemented into the same procedure UPF/USERMAT customization tool [17] of ANSYS standard software. The three-dimensional finite element analysis developed in this paper is specifically devised for addressing the three-dimensional interaction induced by the construction process, twin tunnels proximity, and the presence of the transverse gallery.

In sequence, the outlines the study’s fundamental assumptions and limitations are summarized, followed by the presentation of constitutive models for the rock mass and lining, and the spatial and time discretization for the numerical application. However, before this application, preliminary simulations and verifications with analytical solutions will be presented. Next, the numerical application will then be presented and discussed. This study investigates the effect of the gallery’s presence and twin tunnel proximity on convergence profiles, incorporating nonlinear and time-dependent behavior in the rock mass and lining.