# Introduction

The increasing development of tunnel infrastructures for transportation systems and facilities networks in urban, hilly or underwater environments requires rational and efficient use of underground space, leading in many situations to tunneling nearby existing or new tunnels. The number of deep or shallow twin tunnels excavated in close proximity to each other has notably increased in the last years mainly due to prevailing underground and geotechnical conditions in congested urban areas. Resorting to the solution of twin tunnels, each branch being devised for a flow direction, also presents technical and safety advantages such as the reduction of tunnel diameter. Furthermore, in most cases of adjacent twin tunnels, the construction of connecting transverse galleries is a standard tunnel engineering practice either for safety (emergency exit/access) or functionality (maintenance, service cross-passage) purposes.

The sequence of construction phases of parallel twin tunnels running side-by-side as well as of the transverse gallery is generally dictated by the engineering practice and construction program. The tunnel junctions are usually constructed far behind the advancing face of main tunnel to ensure the excavation of latter slightly affects that of the junction gallery [12, Insam et al. (2019)].

In this context, understanding and assessing the multiple interactions between the components of such a tunnel material system, namely the closely-spaced twin tunnels, the intersecting transverse gallery, the support lining and the ground, is a fundamental and challenging engineering issue that should be handled during the planning stages for optimal design and safety of the whole tunneling operations. Evidence of interaction phenomena in twin tunnels and tunnel junctions have been reported by many case studies (e.g., Pottler (1992), Nyren (1998), Hsiao et al. (2005), Sjöberg et al. (2006), Karakus et al. (2007) [1], Afifipour et al. (2011), Fortsakis et al. (2012) [10], Fargnoli et al. (2015), Li et al. (2016), Elwood and Martin (2016), Connor Langford et al. (2016), Wan et al. (2017), Insam et al. (2019)]. From a structural design viewpoint, the analysis of the complex interaction in such a tunnel system is not an easy task since it inherently involves several factors related to geometry and constitutive characteristics as well as to the prevailing initial mechanical state and the sequence of tunneling. In particular, the computational evaluation of rock deformation and lining loading near the region of tunnel-gallery intersection requires a three-dimensional modeling (e.g., Spyridis and Bergmeister (2015), Chortis and Kavvadas (2021)[12]]. The construction process of the transverse gallery induces a stress redistribution within the surrounding rock mass, which in turn results in additional loading applied to the lining support of the main tunnel. Furthermore, a key aspect of the 3D modeling is the ability to capture the interaction effects on both short-term and long-term structural behavior, which are mainly controlled by the time-dependent rheological behavior of the rock and lining material constituents.

As far as the computational tunnel interaction modeling is concerned, most investigations addressed the configuration of shallow adjacent or twin tunnels (see for instance [1-5, Do et al. (2014), Vlachopoulos et al. (2018), Do et al. (2022), Pedro et al. (2023)], to cite a few recent works), with particular focus on subsurface and surface interaction effects, including evaluation of induced ground settlement. In that respect, a comprehensive review of reference works on related topics may be found in [6].

Referring to the particular configuration of deep-buried tunnels addressed in this paper, the following analytical and numerical contributions to twin tunnels interaction modeling should be quoted. Analytical solutions for the stress distribution around unlined and lined deep circular twin tunnels have been respectively formulated in Guo et al. [9] and Chen et al. [7] within the framework of plane strain assumption considering an elastic behavior for the rock material. It has been found that the interaction between the twin tunnels vanishes when the tunnel spacing exceeds typically two to three tunnel diameters. Similar problem has been studied in Ma et al. [8] who considered unlined deep twin circular tunnels excavated in a homogeneous elastoplastic medium. The approximate analytical solution formulated for the stresses and the plastic zone extent has been verified through comparison with numerical results using FLAC3D software. The authors carried out a parametric study to assess the influence of twin tunnels spacing, rock strength properties and in-situ initial stresses on the shape and extent of the plastic zones.

Several 3D numerical analyses have investigated the mechanical interaction in deep adjacent tunnels (see for instance Chen et al, (2008), [10], Vlachopoulos and Diederichs (2014), Shaofeng (2018), [11], among others). One may refer to [11] for a more exhaustive review on 3D computational approaches dealing with such a problem. Overall, most of these studies emphasized the crucial effect of pillar width on interaction phenomena occurring in the area between adjacent tunnels. The numerical simulations also indicated that the redistribution of strains and stresses induced in the zone between adjacent tunnels by the construction process may be fundamental to devise adequate support/lining system [10,11]. In this context, Chortis and Kavvadas [11] carried out parametric 3D finite element analyses to assess the interaction between deep parallel twin tunnels, with circular and non-circular cross-section, excavated in an elastoplastic rock mass and supported by a linear elastic shotcrete lining. The study focused the interaction analysis on the axial forces that develop in the primary lining of the twin tunnels by considering the effects of geometrical, geotechnical and material constitutive parameters as well as of the construction conditions. In addition, an important conclusion drawn from these studies is that 2D analyses cannot realistically capture the purely 3D interaction nature of the tunneling problem [Vlachopoulos and Diederichs (2014)].

However, few numerical works addressed the interaction phenomena associated with the excavation of transverse gallery connecting the main tunnels. This is mainly due to the fact the numerical simulation of the tunnel junction area would rely on complex 3D geometry discretization together with a large number of calculation steps to provide realistic modeling of the sequentially tunneling process, thus leading to time-consuming procedures. Recent representative works include references [Hsiao et al. (2009), Spyridis and Bergmeister (2015), Li et al. (2016), Liu et al. (2017),[12,14] ]. As reported in [12], the interaction between the transverse gallery and the main longitudinal tunnels significantly modifies the deformation and stress states of the primary support and the surrounding rock mass at the intersection area, making 3D numerical simulations necessary for the realistic design of the such complex structure. It is pointed out that most of the numerical studies were limited to case studies and, as such, cannot be provide design guidelines for more general tunnel junctions. In that respect, on should particularly quote the contributions by Chortis and Kavvadas [12-14] who investigated the mechanical interaction in deep tunnel junction by means of 3D finite element analyses. Based on a comprehensive set of parametric 3D finite element studies, these authors formulated design charts for the axial forces and bending moments acting on the primary support in the intersection zone between the main and junction tunnels.

Existing literature addressing the mechanical interaction in deep twin tunnels with connecting transverse galleries has mainly focus on the response associated with instantaneous reversible/irreversible behavior of the rock mass and lining constituent materials. It is however well established that creep is an essential component of rock deformation in deep tunnels, leading to progressive development of tunnel convergence and lining loading during the construction phase and extending over months or even years. In this context, the purpose of the present study is to investigate the implications of time -dependent constitutive properties of rock and support shotcrete/concrete materials on the short-term and long-term structural behavior. At the material level, the 3D computational model integrates the constitutive state equations formulated for the rock in the framework of coupled plasticity-viscoplasticity, which proves relevant for capturing both irreversible instantaneous response (plasticity) as well as the delayed irreversible response (viscoplasticity). Creep behavior of the lining material, typically shotcrete, is described by means of an aging viscoelastic model that notably accounts for the properties at early age. At the tunnel structure level, the constitutive modeling and related as well as the related numerical integration schemes are developed and implemented within a specific UPF/USERMAT procedure of ANSYS standard software [17]. The finite element modeling developed in this paper can be viewed as specifically devised tool for addressing the three-dimensional interaction induced by the construction process of closely-spaced twin tunnels with transverse gallery junction. The last part of the paper provides several numerical simulations that illustrate the ability to deal with such a problem in highly complex setting and to provide preliminary insight into the involved interactions.

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