# Conclusions

The paper presented a constitutive and computational model for addressing the deformation processes and mechanical interactions in deep twin tunnels with connecting transverse gallery. From the constitutive viewpoint, the irreversible component of rock deformation is modeled within the context of coupled plasticity–viscoplasticity. The latter framework is particularly relevant to describe both instantaneous and delayed deformation in deep clayey rocks. Emphasis has been devoted to the formulation of aging time-dependent constitutive properties of the lining constituent material with account for shrinkage and creep deformation, which are fundamental components of early age and long-term behavior of shotcrete support. At the structure level, the computational modeling integrates the nonlinear and time-dependent constitutive features with implementation of the activation-deactivation technique for simulating the processes of excavation and lining installation. The elaborated model is specifically devised for dealing with three-dimensional finite element analysis of deformation in twin tunnels/transverse gallery system, notably in the perspective of providing technical guidance for safe design of tunnel-gallery junction.

Conceived to provide preliminary insight into the impact of some relevant parameters defining the interaction problem, the numerical simulations undertaken in section 7 notably emphasized that:

1. The deformation anisotropy of the tunnel wall induced by twin tunnel proximity can be significant at both short-term and long-term deformation even when a stiff lining is used. This feature should therefore be integrated in the support design stage.
2. The disturbed region with localized extent near the tunnel-gallery junction, reflecting the strong interaction between these two components of the structure, exhibits peak convergence values that can exceed by a large amount that the convergence far behind the facing. In that respect, the study presents the potential to formulated technical guidance for the design of twin tunnels with transverse gallery.
3. In addition to the effects of coupled plastic-viscoplastic constitutive properties of the rock material, the aging time-dependent behavior considered for the lining concrete/shotcrete has a considerable impact on the short-term and long-term convergence profiles of the tunnel. In particular, the aging viscoelastic lining reveals more efficient in controlling the long-term tunnel convergence than that at short term, which is mainly attributed to the early age properties of constituent material.

Even though the numerical simulations have mainly concerned the situation of deep circular tunnels, the constitutive and related computational model can in its current version be readily applied to analyze more complex configuration exhibiting no particular symmetries as that examined in this paper. In that respect, the following developments may be foreseen in the immediate future:

* The simulation of shallow depth twin tunnels connected or not by transverse galleries, commonly encountered in the urban underground environment and for which the initial stress state should be beforehand properly evaluated. In particular, the modeling should address deformation and design of shallow twin tunnels excavated in horizontal parallel profiles or stacked over each other (e.g., [Islam and Iskander (2021), Do et al. (2022, Chakeri et al. (2011), Do et al. (2016), Do et al. (2014), Do et al, (2015) ]).
* An important aspect to be integrated in the simulations and interaction assessment is related to more realistic tunneling scenario, describing the sequential excavation phase of each component of the underground structure as well as that of the lining placement. A significant impact of the lagged tunnel construction procedure, and more specifically the lagging distance between the faces of twin tunnels as well as of transverse galleries, is notably expected due the time-depend behavior of constituent materials [Islam and Iskander (2021), Do et al. (2016), Ng et al, (2004)]. The numerical modeling and analysis of such configurations is currently the object of ongoing research.

Finally, it should be kept in mind that effective validation of the constitutive and computational modeling remains to be achieved through comparison of the numerical predictions with available experimental and monitoring field data.