# Conclusions

In general, the field of deformations and stresses around a deep tunnel depends on several interrelated factors, including the tunnel depth, anisotropy of in situ stresses, tunnel wall geometry, tunneling conditions, and the mechanical behavior and coupling of the rock mass and the lining. In twin tunnels, there is also the interaction due to the proximity between the tunnels and, if present, transverse galleries, which cause localized stress distribution and overloading the main tunnels. Furthermore, unlike single tunnels, the gallery’s influence can only be studied with three-dimensional models.

One of the contributions of this study at the structural level is the development of a model capable of performing three-dimensional finite element simulations for a domain of deep circular twin tunnels with a transverse gallery. The construction process, including excavation and lining installation, was simulated using an activation/deactivation technique. At the material level, four constitutive models for the rock mass were implemented and investigated: elastic (E), elastoplastic (EP), viscoplastic (VP), and elastoplastic-viscoplastic (EPVP) model. For the lining, three configurations were considered: no lining (NL), elastic (EL), and viscoelastic (VEL) lining. In the numerical application of this study, the influence of different constitutive models was explored, as well as the effect of the spacing between axes of the longitudinal tunnels (, and where is the tunnel radius) and the impact of lining stiffness on deformation control. For time-dependent models (which account for rock mass creep and lining creep and shrinkage), results were obtained and analyzed at the end of tunnel construction (short-term - ST) and after viscous effects had reached equilibrium (long-term - LT).

However, before this application, preliminary numerical simulations of the 3D computational model were carried out, and comparisons were made with analytical solutions for unlined twin tunnels under plane strain conditions, considering both elastic and elastoplastic rock mass. These simulations demonstrated the model’s capacity to accurately capture the main effects occurring in such structures, including the ovalization effect, stress distribution, and the extent of the plastic zone, for various tunnel spacing, initial in situ stresses, and different values of cohesion and friction angle.

Regarding the application of this study, the main objective was to demonstrate the capability of the proposed formulation to address the three-dimensional problem of twin tunnels connected to galleries, involving nonlinear and time-dependent behaviors. However, a comprehensive parametric analysis that integrates the effects of geometric, constitutive, and loading parameters is beyond the scope of this specific numerical application. Constitutive parameters were selected for deep clay rockmass (at a depth of 450 m) from the eastern Paris basin, based on laboratory tests conducted under undrained conditions, which exhibited both instantaneous and delayed behavior and could be simulated by the implemented constitutive models. For the lining of both the twin tunnels and the gallery, a constitutive model values was used that takes into account the creep and shrinkage of concrete, through a viscoelastic aging model.

Considering the constitutive parameters and tunneling conditions adopted, some conclusions from this study can be highlighted. First, when comparing the convergence profiles, the difference between short-term and long-term responses is more pronounced when the lining is viscoelastic. This demonstrates the importance of adopting a model that accounts for concrete creep and shrinkage. The relatively high stiffness of an elastic lining significantly reduces the viscous deformations of the rock mass. In the short-term, the early age of the lining results in a lower relaxation modulus compared to the constant 28-day modulus used for the elastic lining. In the long-term, although the viscoelastic lining shows an increase in the relaxation modulus due to the aging phenomenon, the creep of both the rock and the lining components results in significantly greater convergences compared to models that do not consider time-delayed effects.

Additionally, the results indicate that the ovalization effect on the tunnel wall, caused by the proximity between the tunnels, is more pronounced in the short-term. Results with elastic lining showed that, over time, the viscosity of the rock mass tends to reduce this ovalization effect. The impact on tunnel convergence, due to the proximity of the tunnels and the time required for the complete excavation of the gallery, which also depends on this distance, was most significant for . This distance resulted in the highest peak convergence value at the roof of the longitudinal tunnel, located at the intersection of the twin tunnels and the gallery axes, represented by . Furthermore, a significant increase in the magnitude of between the short-term and long-term responses was observed, due to the influence of the time-dependent behavior of the rock and the concrete lining.

To assess the effect of the lining stiffness on deformation control, complementary analyses were carried out by reducing the lining thickness from (higher stiffness) to (moderate stiffness). Considering the elastoplastic behavior of the rock mass and elastic lining, the stiffer lining resulted in a 35% reduction in convergence compared to the unlined structure, while the moderate stiffness lining reduced convergence by only 12%. Regarding the influence zone of the gallery on the longitudinal tunnel convergence profile, it was observed that increasing the stiffness reduced the extent of this zone in all studied configurations (, without lining, and for stiffer and moderate stiffness lining, respectively, where is the gallery radius). However, the spacing between the tunnels had little impact in extent of this zone. In terms of the displacements magnitude due to the presence of the gallery, in the configuration with the largest spacing , where less interaction between the twin tunnels is expected, the relative variation between the peak convergence and the convergence outside the gallery’s influence zone was approximately 14% for the unlined structure, 12.5% for the moderate stiffness lining, and 8.7% for the stiffer lining. These values were reduced to 9.7%, 13%, and 12%, respectively, for the spacing of , where the effects of lining stiffness and tunnel proximity occur simultaneously.

When the rock mass is elastoplastic-viscoplastic, long-term results suggest that the extent of the gallery’s influence zone is also not affected by the distance . However, the difference between the peak convergence and the convergence outside of this influence zone is significantly influenced by and the stiffness of the lining. For an elastic lining, this difference is 12% for and 18% for . This confirms that the effect of tunnel proximity on peak convergence is predominant. However, when the lining is viscoelastic, the stiffness of the lining significantly influences this difference. For , the values are 9.5% for the moderate stiffness lining and 13% for the stiffer lining. For , these values are 14.5% and 18%, respectively, indicating the complex interaction between tunnel proximity, the gallery, and constitutive behaviors.

Although the conclusions are constrained by the validity of the models, the parameters adopted, and the tunneling conditions (such as the simultaneous excavation of longitudinal tunnels at a constant speed) the formulation and domain discretization employed proved effective in producing analyses involving twin tunnels with transverse gallery. However, additional validations through case studies are necessary to support the results of this study. Nonetheless, future developments are important and could expand this study. From a structural level, other tunneling conditions can be considered, such as the lagged distance between tunnels face or examining the impact of the proximity of these faces on the convergence of the gallery. Another aspect, relevant to time-dependent behavior, is to simulate the excavation of the tunnels and gallery with variable excavation speeds. On a material level, incorporating the effects of rock pore pressure and rock bolts through homogenization technique would improve the analysis.