Dear Dr. Quevedo,

We have received the reports from our advisors on your manuscript, "Numerical analysis of the rock deformation in twin tunnels with transverse gallery considering plasticity and time-dependent constitutive models", which you submitted to Geotechnical and Geological Engineering.

The manuscript number is GEGE-D-24-01227

Based on the advice received, I feel that your manuscript could be reconsidered for publication should you be prepared to incorporate major revisions.

When preparing your revised manuscript, you are asked to carefully consider the reviewer comments which are attached, and submit a list of responses to the comments.

Submit your response as separate submission item.

PLEASE VISIT THE WEBSITE FOR POSSIBLE REVIEWER ATTACHMENTS

In order to submit your revised manuscript, please access the Editorial Manager Website.

Your username is: fel\_quevedo

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We look forward to receiving your revised manuscript within eight weeks.

With kind regards,

Jia-wen Zhou, Ph.D.

Associate Editor

Geotechnical and Geological Engineering

**COMMENTS TO THE AUTHOR:**

**Reviewer #2:** The research work is based on pure theoretical derivation and simulation analysis. Many mature commercial software has good calculation and analysis functions. Therefore, the innovation of the research work is insufficient, and the practical guiding role of the project is insufficient. In addition, there are too many sections and too long length. It is suggested to carry out targeted research on an innovative problem to avoid lengthy discussion. Unfortunately, the existing manuscript cannot be supported.

Dear Reviewer,

Thank you for your thorough feedback on our manuscript. We appreciate your observations and would like to address the concerns raised:

1. Innovation and Practical Guiding Role

While we acknowledge that the study relies on theoretical derivation and simulation analysis, our focus was to address a specific gap in the literature: the coupled effects of time-dependent material behavior, twin tunnel proximity, and transverse gallery interaction on deformation profiles. To our knowledge, the integration of advanced constitutive models, such as coupled plasticity-viscoplasticity for rock and aging viscoelasticity for lining materials, into a fully three-dimensional finite element framework is not comprehensively addressed in existing studies. Moreover, the findings highlight critical design considerations, such as deformation anisotropy and peak convergence values at tunnel-gallery junctions, which provide valuable insights for safe and efficient design of complex underground structures.

1. Use of Commercial Software

While commercial software provides robust tools for general calculations, our study required custom implementation of constitutive models and excavation simulations tailored to the unique configurations of twin tunnels with transverse galleries. These extensions were necessary to capture the specific interactions and time-dependent behaviors that are often oversimplified or unavailable in standard commercial solutions.

1. Manuscript Length and Structure

We agree that the manuscript's length and number of sections may appear extensive. However, this was intended to provide a comprehensive and detailed exploration of the topic. Based on your feedback, we will streamline the discussion, remove redundancies, and focus more on the key findings to enhance readability and conciseness.

Targeted Research on an Innovative Problem

We appreciate your suggestion to focus on a more targeted innovative problem. We believe the coupling of plasticity-viscoplasticity and viscoelasticity in the context of three-dimensional simulations already offers a novel contribution. Nonetheless, we will refine the manuscript to better emphasize the innovative aspects of our work and clarify its relevance to practical tunneling challenges.

We value your constructive comments and will use them to improve the manuscript significantly. We hope that these revisions will address your concerns and allow for reconsideration of the study.

Thank you for your time and valuable input.

**Reviewer #5:**

In this manuscript, the authors study rock deformation in twin tunnels with a transverse gallery, considering plasticity and time-dependent constitutive models. After reviewing the manuscript, I believe the following questions should be addressed in the revised version:

**1) The title could be changed to "Evaluation of Rock Deformation in Twin Tunnels with a Transverse Gallery, Considering Plasticity and Time-Dependent Constitutive Models."**

**2) Is the twin tunnel mentioned in Section 5 an actual case study? If so, the geotechnical properties, as well as details regarding the size, excavation method, and lithological units of the study area, should be provided.**

The twin tunnel mentioned in Section 5 is not a case study, but an academic configuration used to validate and demonstrate the application of the developed numerical model. The geometrical properties, material parameters, and boundary conditions were defined based on data from the literature and some assumptions (referred in Section 2). There are no specific twin tunnels with geotechnical data, excavation methods, or lithological unit details, as the study aims to explore generic scenarios of interaction between twin tunnels and a transverse gallery.

To make it clearer, this point has been incorporated into Section 5: "Spatial and Time Discretization of the Domain", immediately after introducing the model geometry and conditions, with the following text:

"The twin tunnel configuration is an academic setup designed to validate and illustrate the applicability of the proposed numerical model. The geometric parameters and boundary conditions are common to twin tunnels configurations and the material properties were based on data from the literature (see section 7.1), and do not correspond to a specific case study."

**3) Which software was used for simulating the tunnel?**

The software used was ANSYS, but it is important to note that the constitutive models (for the rock mass and lining) were implemented within it using the UPF/USERMAT resource. The software doesn't have these models.

This information is in the text of the article:

The seventh paragraph in Section 1:

“[…] 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 (ANSYS 2018). 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. […]”

For the rock mass, in the last sentence of the first paragraph in Section 3:

“[…] Detailed description of the model, including application and validation in the context of single tunnel structures may be found in Quevedo et al. 2022b. Finite element implementation of this model in the USERMAT procedure of ANSYS software is also described in Quevedo 2021.”

And for the lining, in the last sentence of the first paragraph in Section 4:

“[…] Full details regarding model definition and related finite element implementation may be found in Quevedo 2017 and Quevedo et al. 2022a.”

However, to make it clearer will be added in section 1, last paragraph:

“The simulations presented in this study were conducted using the ANSYS software suite, a widely used finite element analysis tool. To address the specific requirements of the research, custom user-defined material models (USERMAT) were implemented within ANSYS to capture the coupled plasticity-viscoplasticity behavior of the rock and the aging viscoelastic properties of the concrete lining. This approach allowed us to go beyond the standard capabilities of commercial software, enabling the accurate representation of time-dependent material behaviors.”

**4) How was the numerical model calibrated?**

**5) How were the results of the numerical simulation verified?**

The results of the numerical simulations were verified by comparing them with analytical solutions and numerical results available in the literature for similar configurations without transverse gallery. For example, comparisons were made with the analytical stress solutions for twin tunnels under plane strain conditions proposed by Guo et al. (2021) and Ma et al. (2020). Preliminary numerical tests were conducted to evaluate the accuracy of the finite element implementation, including stress distributions and plastic zone boundaries. These comparisons demonstrated the ability of the model to capture the key interaction effects and deformation mechanisms.

**6) The support systems of the tunnels and gallery should be clearly presented in a specified table.**

This is presented in Table 1.

**7) The boundary conditions, assigned material properties, and model size should be illustrated in the text.**

Boundary conditions are detailed in Section 5 and illustrated in Figure 5, including the geostatic initial stresses (Equation 11) and symmetry conditions. The model size is described in third paragraph of Section 5, with domain dimensions and mesh details shown in Figure 5 and Table 1. Assigned material properties are provided in Section 7.1 and summarized in Table 2, covering both rock mass and lining parameters.

**8) How were the normal and shear stiffness between the initial and secondary support systems considered in the model?**

The concrete lining is modeled as a continuous structure with constant thickness, without distinguishing between primary and secondary support systems. The interaction between the support and rock mass was modeled assuming perfect bonding, eliminating the need to explicitly consider normal and shear stiffness. This simplification is valid for scenarios with good material connection. For interfaces with potential sliding or separation, advanced interface models with specific parameters could be applied.

This response can be incorporated in Section 2: "Fundamental Assumptions":

"The lining was modeled as a continuous structure, assuming perfect bonding with the rock mass and without distinguishing between primary and secondary supports. This simplification avoids explicitly modeling normal and shear stiffness and is valid for scenarios with strong material connections."

and eliminate the eight item:

"Perfect bonding is assumed at the interface between concrete lining and the rock mass."

and change the sixth item:

"The simulation excavation processes are curried out assuming a constant tunnel advancement rate (i.e., constant excavation speed), together with a constant thickness of concrete lining."

to:

"The simulation excavation processes are curried out assuming a constant tunnel advancement rate (i.e., constant excavation speed)."

**Reviewer #6:** The paper is good and worthy explaining the finite element analyses of the twin circular tunnels deformation mechanisms taking into account the visco-elasto-plastic behavior of the surrounding rocks. the following comments are suggested:

**1- Title of the paper may be revised as the numerical modelling analyses are based on the FEM. For example the following title is suggested: "A three-dimensional finite element analysis of the rock deformation mechanisms in twin circular tunnels with a transverse gallery based on visco-elasto-plastic constitutive models".**

**2- The English of the abstract may be rechecked. Some lengthy and somewhat repetitive sentences exist.**

The original abstract:

“Resorting to a three-dimensional finite element framework, the paper investigates the instantaneous and long-term deformation in twin tunnels with connecting transverse gallery. Particular emphasis is dedicated to the assessment of combined effects induced by time-dependent behavior of the material constituents, twin tunnels proximity and tunnel junctions on the convergence profile. At the material level, the rock mechanical behavior is formulated within the context of coupled plasticity–viscoplasticity, which proves relevant for modeling and simulation of tunnel deformation in deep clayey rocks. As regards the time-dependent properties of the lining concrete, the concrete creep deformation is addressed by means of an aging viscoelastic model relying on the Bažant and Prasannan Solidification Theory, whereas shrinkage deformation component is based on the formulation proposed in CEB-FIP MC90 standard. At the structure level, the deactivation-activation technique is employed in the three-dimensional finite element model to simulate the excavation/advancing face and lining installation processes. The accuracy of the approach predictions is assessed through comparisons with available analytical stress solutions formulated within a simplified setting for the twin tunnels configuration. The computational model is applied to analyze the short-term and long-term convergence profiles in a fully 3D twin tunnels framework, providing preliminary insight into the multiple interactions arising from twin tunnel proximity, intersecting transverse gallery and lining support. The numerical simulations have notably emphasized the deformation anisotropy induced by tunnels proximity, the peak convergence values observed at tunnel-gallery junction as well as the crucial role of time-dependent properties of concrete lining in controlling the tunnel deformation.”

Was modified to:

“Resorting to a three-dimensional finite element framework, the paper investigates the instantaneous and long-term deformation in twin tunnels with connecting transverse gallery. Emphasis is dedicated to the combined effects of time-dependent materials behavior, twin tunnels proximity, and tunnel junctions on the convergence profile. At the material level, the rock's mechanical behavior is modeled through coupled plasticity-viscoplasticity, suitable for deep clayey rocks. As regards the lining concrete, the creep deformation is represented by an aging viscoelastic model based on Bažant and Prasannan's Solidification Theory, while the shrinkage deformation component is based on the formulation proposed in the CEB-FIP MC90 standard. At the structure level, the excavation and lining installation are simulated through the activation-deactivation technique. The model's accuracy is assessed through comparisons with available analytical stress solutions for simplified twin tunnel configurations. The numerical simulations have notably emphasized the deformation anisotropy induced by tunnels proximity, the peak convergence values observed at tunnel-gallery junction as well as the crucial role of time-dependent properties of concrete lining in controlling the tunnel deformation.”

**3- The theoretical background and literature review on the stress analyses around rock tunnels may be improved. For example see the following papers:**

Thank you for your valuable suggestion regarding the theoretical background and literature review on stress analyses around rock tunnels. We appreciate the recommended references and agree that they provide insightful perspectives that can strengthen the context of our work. We will incorporate these studies into the revised manuscript, specifically in the introduction and literature review sections, to provide a more comprehensive overview of stress analysis techniques and their relevance to time-dependent behavior in tunnel systems.

N Nikadat, MF Marji, 2016, Analysis of stress distribution around tunnels by hybridized FSM and DDM considering the influences of joints parameters, Geotechnical and Geological Engineering 11 (2 (April 2016)), 269-288.

Abstract:

The jointed rock mass behavior often plays a major role in the design of underground excavation, and their failures during excavation and in operation, are usually closely related to joints. This research attempts to evaluate the effects of two basic geometric factors influencing tunnel behavior in a jointed rock mass; joints spacing and joints orientation. A hybridized indirect boundary element code known as TFSDDM (Two-dimensional Fictitious Stress Displacement Discontinuity Method) is used to study the stress distribution around the tunnels excavated in jointed rock masses. This numerical analysis revealed that both the dip angle and spacing of joints have important influences on stress distribution on tunnel walls. For example the tensile and compressive tangential stresses at the boundary of the circular tunnel increase by reduction in the joint spacing, and by increase the dip joint angle the tensile stress in the tunnel roof decreases.

Buy article.

M. S. Abdollahi, M. Najafi, AR Yarahmadi Bafghi, MF Marji, 2019, A 3D numerical model to determine suitable reinforcement strategies for passing TBM through a fault zone, a case study: Safaroud water transmission tunnel, Iran,Tunneling and Underground Space Technology 88, 186-199.

Abstract

Mechanized tunneling, like other tunneling methods, is not an exception to dealing with complex geological structures in its direction. Therefore, the accurate perception of the geological structures and anomalous through the tunnel path and the challenges ahead of TBM can minimize the operational risk. The faults are complicated, loose, seismic, and saturated structures that present a great deal of danger when passing the tunnel from them, and each of these events, in turn, has the potential to stop the project and exert high economic costs. The instability of the tunnel environments and tunnel face due to the higher amount of stress concentration than the resistance of the host rock, pulpy material flowing from inside of the faults and water inrush are the most important events that TBM faced them through the fault zones. Hence, using the appropriate tool for realizing the operational model can be a considerable help in predicting problems. In this research, using precision numerical methods, accurate simulation of TBM motion was carried out to the excavation of Water Transmission Tunnel, Iran. The Safaroud water transmission tunnel is one of the longest Iranian water transmission tunnels that passes through numerous fault zones along its path. One of the main faults in this area is the Lalehzar fault with 40 m width which motivates us to utilize predicting procedure. The main purpose of this research is numerical modeling of mechanized tunneling in fault zone using FLAC3D and Phase2 software and selection of suitable reinforcement strategies for passing TBM from the fault zone. The results of numerical modeling illustrate the instability of the tunnel in the Lalehzar fault zone. Due to tunnel instability in this zone, reinforcement operations must be taken into account to stabilize the tunnel environment. The numerical modeling of the several reinforcement operations in the fault zone were simulated and we conclude that the combination of umbrella arch and radial grouting method are the most suitable strategies for passing TBM from the Lalehzar fault zone.

https://www.sciencedirect.com/science/article/pii/S0886779818305078

A Abdollahipour, MF Marji, AY Bafghi, J Gholamnejad, 2016, Time-dependent crack propagation in a poroelastic medium using a fully coupled hydromechanical displacement discontinuity method, International Journal of Fracture 199, 71-87.

Abstract:

Many problems in subsurface rocks which are naturally filled with saturated cracks and pores (with one or more fluid phases) are better understood in a poroelastic framework. Displacement discontinuity method (DDM) is particularly ideal for problems involving fractures and discontinuities. However, the DDM in its original form is limited to elastic problems. The paper derives fundamental solutions of a poroelastic DDM. Then introduces a numerical formulation and implementation for the poroelastic DDM in a code named constant element poroelastic DDM (CEP-DDM). The accuracy and validity of the proposed solution and the newly developed code is verified by an analytical solution at short-time and long-time. Numerical results showed good agreement with analytical results at short time (undrained response) and long time (t = 8000 s) (drained response). A crack propagation scheme for crack propagation problems is introduced and demonstrated in an example which enables the code to follow crack propagation in time and space.

https://link.springer.com/article/10.1007/s10704-016-0095-9

A Abdollahipour, MF Marji, AY Bafghi, J Gholamnejad, 2016, A complete formulation of an indirect boundary element method for poroelastic rocks, Computers and Geotechnics 74, 15-25.

Abstract

Rocks are naturally filled with cracks and pores that are saturated with one or more fluid phases. Many problems in rock mechanics, petroleum engineering, geophysics, etc. deal with cracks and discontinuities in rock formations. These problems should consider effects of a porous medium. Displacement discontinuity method (DDM) as an indirect boundary element method is particularly ideal for problems involving fractures and discontinuities. However, the DDM in its original form is limited to elastic problems. The paper uses a fundamental solution of a point displacement discontinuity in poroelastic medium to obtain the solution for a poroelastic DDM. Then it introduces a numerical formulation and implementation for the poroelastic DDM in a code named CEP-DDM (Constant Element Poroelastic DDM). The accuracy and validity of the proposed solution and the newly developed code are verified by two analytical solutions, another numerical solution, and some field measurements. These results showed good agreement between CEP-DDM and other methods’ results. The verifications prove the accuracy and applicability of the proposed numerical model in a wide range of real-world problems.

https://www.sciencedirect.com/science/article/pii/S0266352X15002748

The citation of these articles was incorporated in second item of the Fundamental Assumptions:

“Although material heterogeneity and behavior anisotropy are inherent features of soils and rocks, the rock mass is modeled throughout the paper as a homogeneous and isotropic continuous medium. At the scale adopted for tunnel modeling (macroscopic scale), this assumption means in particular that the possible micro-heterogeneities, such isotropic distributions of joints or cracks present at the finer scale, are accounted for in the homogenized behavior by means of a preliminary homogenization process (e.g., Nemat-Nasser and Hori 1993, Deudé et al. 2002, de Buhan et al. 2002, Marmier et al. 2007, Aguiar and Maghous 2023). Clearly enough, the framework of continuum modeling adopted in the paper would reveal questionable when the rock mass is cut by a few macroscale fracture joints. Exemplos de estudos que lidam com fratura em macro escala são…”

**4 - The explanations for Figures' captions may be improved, For example the caption of Figs. 11 is very concise. It may be divided into two parts (a) and (b) for the two figs, and explain them individually., The same is true for Figs. 19 and Figs. 20, etc..**

Figure 11 has been modified to indicate a) and b), with the legend:

“Fig.11. Schematic representation of the excavation and lining installation process in the a) longitudinal tunnel and b) transverse gallery.”

The legend of the Figure 19 has been modified to:

“Fig. 19: The plastic zone extent obtained from the present F.E. simulations and from the stress solution provided in Ma et al. 2020 considering different rock cohesion values and initial stress states.”

Figure 20 has been modified to indicate a), b) and c), with the legend:

“Fig 20: Comparison between F.E. simulations and the analytical solution by Ma et al. 2020 for radial and orthoradial stress components along different radial paths: a) theta 45, b) theta 90 and c) thetha 135.”

**Reviewer #7:** This paper conducted numerical analysis of the rock deformation in twin tunnels with transverse gallery. Overall, this paper is interesting. The following comments are for the authors to consider. After revision, I think this paper can be published.

**(1) In the introduction, the authors mentioned that tunnels are widely used and in the underwater environment. Therefore, the latest research regarding the interaction between rock mass around tunnels and water is recommended to be added (10.1016/j.engfailanal.2024.109137).**

Abstract

To study the groundwater influence on the mechanical properties of deep hard rock semi-circular arch tunnels with straight walls, compression experiments were conducted on semi-circular arch tunnel samples treated with soaking. The hydraulic damage and failure behaviour of semi-circular arch tunnels with straight walls under soaking conditions is analysed. The peak stress and stiffness decreased gradually with soaking time. These mechanical properties of samples softened significantly. Compared with those of the natural samples, the pre-peak plastic deformation of the water-soaked samples is larger and the plasticity is stronger. Under high vertical stress, the left and right sidewalls of all samples show the spalling failure character from the shallow section to the deep section. During the accumulation and releasing of elastic strain energy, initial failure typically occurs at arch corners. Moreover, this failure location is not affected by water. The sample failure process under uniaxial loading can be divided into quiescent period, particle ejection period, accelerated crack expansion period and formation period of symmetrical “V”-shaped groove failure zone. The low acoustic emission (AE) energy and high AE energy events occur sequentially with loading time. This phenomenon reflects the gradual increasing in the AE energy concentration within samples. Under uniaxial loading, the influence of water–rock interaction on crack generation and expansion is significant. The longer the soaking time is, the more obvious the influence is. The damage variable increases rapidly firstly. Then, it becomes slow. Finally, it increases rapidly with strain.

https://www.sciencedirect.com/science/article/pii/S135063072401183X

**(2) For the fundamental assumptions, this section can be shortened.**

**(3) Please further check whether some equations or figures should be cited in Section 3, such as Figure 1 and Equation (2).**

The authors considered Figure 1 and Equation (2) important for understanding the mathematical description of the model.

**(4) The above comment is also applicable to section 4.**

The authors considered Figure 3 and equations important for understanding the mathematical description of the model.

**(5) When author mesh the geometry to the corresponding number of elements, which guideline did the authors follow? I mean how did the authors determine the corresponding number of elements?**

The mesh density and element distribution in our study were defined based on a balance between accuracy and computational efficiency. We followed standard meshing practices for geotechnical problems, ensuring that the element size was sufficiently small in regions of high stress gradients, such as near the tunnel-gallery intersections. A mesh convergence study was performed, wherein we progressively refined the mesh and monitored key results (e.g., stress distribution and convergence profiles) until changes between successive refinements were negligible. Special attention was given to areas with complex interactions, such as the transverse gallery and surrounding rock mass, where 10-node tetrahedral elements were used to capture detailed stress redistribution. For the remaining structure, 8-node hexahedral elements were employed to optimize computational costs. The final number of elements was also influenced by the computational resources available, as we aimed to ensure the feasibility of running multiple simulations for different parametric studies.

To make it clearer, it will be added in section 5:

“The mesh density was determined based on a balance between accuracy and computational efficiency. A mesh convergence study was conducted comparing the results, such as stress distributions and displacements, between successive mesh refinements until changes were negligible. The results also were verified with analytical solutions presented in the following section.”

**(6) The authors conducted a comprehensive analysis and parameter study. However, it will be better to compare the numerical study with some in-situ tunnelling cases. I understand that the fundamental research will be quite difficult to have certain in-situ tunnelling cases. Therefore, this is a recommendation for the authors to consider.**

We sincerely thank you for your valuable comment highlighting the importance of comparing numerical study with in-situ tunneling cases. We fully agree that such comparisons are critical for validating and enhancing the practical applicability of the research findings.

As noted, the primary focus of this study is on fundamental research and the development of a robust numerical approach to model the interactions between twin tunnels and transverse galleries with delayed effects. While the current work does not incorporate specific in-situ cases due to limitations in accessing detailed and well-documented project data, we emphasize that the developed methodology is designed to be applied in future analyses of real tunneling projects.

We acknowledge the significance of this recommendation and are actively exploring opportunities to collaborate with tunneling projects to validate the computational model using field data in subsequent research. Thank you once again for your insightful suggestion, which we believe will be an important direction for future studies.

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