Time-dependent deformation analysis of the surrounding rock mass around a tunnel

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Abstract. A numerical time-dependent model is established by incorporating the stress corrosion model into the three-dimensional discrete element grain-based model (3DEC-GBM) to analyze the fracture evolution and instability mechanism of the surrounding rock mass around a circular tunnel. The surrounding rock of the tunnel is assumed to be made from intact Yunnan sandstone formation, whose material properties were found using laboratory experiments (ignoring scale effects). The mesoscale mechanical stress corrosion parameters in the model are calibrated to reproduce the time-independent and -dependent deformation and failure of Yunnan sandstone observed in a laboratory. The model is validated against laboratory data and then further applied to analyze the time-independent and -dependent deformation of the surrounding rock of the tunnel. The fracture evolution around the tunnel instability is numerically visualized. The failure zone around the tunnel gradually extends deeper into the surrounding rock with time, and the location of failure at the roof and floor of the circular tunnel becomes more evident as the lateral pressure coefficient increases. We conclude that the model is not only able to simulate the location of the concentrated tensile and shear stress around the tunnel but also has important theoretical guidance and practical significance for the long-term stability study of tunnels.

Key words: time-dependent deformation; stress corrosion model; Yunnan sandstone; circular tunnel

1 Introduction

Deformation and fracture around underground openings are widely observed, particularly under high and complex in-situ stress. The release of preexisting stress that results from the excavation of an underground opening disturbs the state of equilibrium of surrounding rock. The excavation boundary acts as the predominant source of stress concentration tangent to the opening in these cases. When the local stress near existing flaws exceeds the strength threshold of the rock, cracks start to develop from them. Propagation and coalescence of the cracks eventually lead to significant deformation and macroscopic failure around the opening and result in a zone of stress relaxation of the surrounding rock around the opening. After the excavation has been completed, the convergence of the surrounding rock masses may continue to increase as time (e.g., months or years) passes because of rheological behavior, which greatly effects the determination of the support method for the underground opening. These observations suggest that a thorough understanding of...
time-independent and -dependent deformations around an underground opening is essential for their design and construction under in-situ stress condition.

This paper aims to simulate fracture evolution around a circular tunnel under varying lateral pressure coefficients at mesoscale. A three-dimensional discrete element grain-based model (3DEC-GBM) was built to reproduce the surrounding rock made into Yunnan sandstone, which consists of Voronoi grains with variable sizes and shapes. We simulated the time-dependent deformation of the studied sandstone by applying a rheological model with the use if the stress corrosion law to calibrate mesoscale mechanical parameters and stress corrosion parameters on the basis of laboratory tests. We then explored the time-independent and -dependent fracture evolution around the circular tunnel under varying lateral pressure coefficients.

2 Numerical approach

2.1 Time-dependent model

3DEC-GBM was built using 3-Dimensional Distinct Element Code (3DEC) by Itasca Consulting Group) in this study. The model comprised an assemblage of Voronoi grains with varying shapes and sizes generated in Neper\(^9\), which can more reasonably describe the random properties and the internal structure of the rock mass compared with the regular tetrahedron tessellation\(^10\)-\(^12\). For example, a numerical cylindrical sample shown in Fig 1, which comprises an assemblage of grains of differing shapes and sizes, was built using 3DEC. It has the same dimensions as the samples (a diameter of 50 mm and a height of 100 mm) used in the laboratory experiments in this paper. The sample contains 5,300 Voronoi polyhedron grains, and all grains in the sample are convex polyhedrons. The model allows for arbitrary displacement and rotation of the grains, as well as separation of the grains along their contacts.

In this study, Voronoi grains were assumed to be deformable and made linear elastic without an ultimate strength. The contacts between the deformable grains were assigned the Mohr–Coulomb shear failure criterion and Rankine’s maximum tensile stress criterion. The microcracks form only along the contact between the grains and could not penetrate and break the grain. The stress corrosion law was further incorporated into 3DEC-GBM to simulate the progressive fracture process and time-dependent deformation of rock\(^7\). Each sub-contact, which automatically formed after the entire grain is zoned, is a potential stress-dependent corrosion site where microcracks form and propagate. The values of tensile strength and cohesion of the sub-contacts reduce with the stress corrosion rate. Hence, the formulation that expresses the stress corrosion rate \((v_\text{cl})\) of the sub-contacts is given by

\[
v_{cl} = \begin{cases} 
0 & \bar{\sigma} < \sigma_0 \\
B_1 e^{B_2} & \sigma_0 \leq \bar{\sigma} < \sigma_c \\
\infty & \bar{\sigma} > \sigma_c 
\end{cases}
\]

where \(B_1 = AV_0 e^{-(E^*+v_\text{cl}RT)/RT})\) and \(B_2 = v^+/RT\), \(v_0\) are the pre-exponential factors, \(v^+\) is the activation volume, \(\sigma\) is the crack tip’s tensile stress, \(R\) is the universal gas constant, \(E^*\) is the stress-free activation energy, \(v_M\) is the molar volume of the glass, \(\gamma\) is the interfacial surface energy between the glass and the reaction products, \(T\) is the absolute temperature, and \(\rho\) is the radius of curvature of the crack tip. \(A\) is the constant of proportionality between the chemical reaction rate and the degradation rate, \(\sigma_0\) is the threshold stress\(^13\), and \(\sigma_c\) and \(\sigma\) are the peak strength and the reaction-site stress, respectively\(^7\). Meanwhile, the timestep within the time-dependent model represents real time. The self-adaptive procedure was used to automatically adjust the timestep on the basis of out-of-balance force criteria\(^14\).
Fig. 1 Cylindrical sample showing the polyhedral-shaped elements (left), a section of the cubic sample showing the roughness of an internal surface (potential fracture plane) (right), and a bond between two polyhedral grains (right).

2.2 Laboratory tests on sandstone
We assumed that the surrounding rock of the circular tunnel is intact Yunnan sandstone, and no macroscale discontinuities were considered. Yunnan sandstone was collected in Yunnan (China). The mineral composition of this sandstone is approximately 60% quartz, 19% feldspar, 8% calcite, and 13% cement, and its average density is 2,119 kg/m³. A number of cylindrical Yunnan sandstone specimens with a diameter of 50 mm and a height of 100 mm were prepared from a single block. No macroscale defects, such as fractures, were observed in any of these specimens. Uniaxial compression tests were conducted on Yunnan sandstone by using a 2000 kN capacity TAW testing machine (Fig. 2). A constant displacement rate of 0.0025 mm/s, which is equivalent to an axial strain rate of $2.5 \times 10^{-5}$ s⁻¹, was axially loaded on the specimen during compression. The lateral deformation was measured using a roller-chain circumferential extensometer mounted at the mid-height of the specimen. The axial deformation was measured directly by three extensometers mounted directly on the specimen. Uniaxial compressive creep tests were performed by axially loading the specimen at a constant displacement rate of 0.0025 mm/s to a predefined stress level, which was held constant until the specimen underwent failure.

Fig. 2 TAW rock test mechanics

2.3 Model calibration
Numerical cylindrical specimens that have the same dimensions as the laboratory specimens described in this paper were generated to deform numerically in uniaxial compression simulations and uniaxial compressive creep simulations. The mesoscale parameters of the numerical specimens were calibrated using a trial-and-error method, which has been applied in the literature. A series of numerical simulations (e.g., uniaxial compressive simulation) was performed to find the best design mesoscopic parameter for the studied sandstone. The results are listed in Table 1, indicating
that the numerical model represents the deformation and failure behavior of the samples observed in laboratory experiments. The peak stress and the elastic modulus of the numerical samples are 52.1 MPa and 11.5 GPa, respectively, which are the same as the laboratory experiment results. A series of numerical creep simulations was further performed based on uniaxial compression creep tests to determine the best design subcritical crack parameters. The values are $B_1 = 4.3 \times 10^{-4}$ and $B_2 = 3.5 \times 10^{-7}$.

| Table 1. Calibrated mesoscale parameters of the sandstone simples. |
|---------------------------------------------------------------|
| Properties | Values |
| Young’s modulus ($E$, GPa) | 12 |
| Poisson’s ratio ($\nu$) | 0.27 |
| Normal stiffness ($K_n$, GPa·mm$^{-1}$) | 40 |
| Shear stiffness ($K_s$, GPa·mm$^{-1}$) | 20 |
| Tensile strength ($J_T$, MPa) | 7.6 |
| Cohesion ($J_c$, MPa) | 31.2 |
| Friction angle ($\varphi$, °) | 27 |
| Residual friction angle ($\varphi_r$, °) | 6 |

3 Modeling of progressive fracturing processes of tunnel

3.1 Numerical model of tunnel

A numerical model with a simple geometry of $20 \times 20 \times 7$ m was built to simulate the fracture evolution around the circular tunnels after excavation under varying lateral pressure coefficients. The shape was circular, and the diameter of the tunnel was 3 m. The model consisted of 80,000 Voronoi polyhedron grains (Fig. 3a). The model was simplified to study plane strain problems because of the limit of computing time and the neglect of the influence of staged excavation process on the deformation and failure of the surrounding rock. Hence, a small thickness (0.05 m) of the tunnel model was considered in the Y-direction, and the equivalent size of grains was 0.05 m (Fig. 3[b]). The support systems were not considered by the numerical analysis to enable an understanding of the fracture evolution of surrounding rocks of the underground opening under different lateral pressure coefficients. The progressive fracture processes of time-independent and -dependent simulation of the tunnel after excavation were presented in this paper. The bottom boundary of the tunnel model was fixed in the Z-direction. Four cases were considered in the model: the vertical stress $P_2$ was constant at 40 MPa, and the horizontal stresses $P_1$ were 0, 20, 40, and 60 MPa, which correspond to the lateral pressure coefficient $\lambda$ of 0.0, 0.5, 1.0, and 1.5, respectively. Our model is not intended to build a realistic model of this specific tunnel, which has many additional features. Instead, our model attempts to use only the geometry and assumes that the surrounding rock of the tunnel is composed of intact Yunnan sandstone, with the mesoscale parameters listed in Table 1 (ignoring scale effects).
3.2 Time-independent response of tunnel

Deformation and failure of the tunnel occur and then gradually become constant after excavation. The simulated time-independent deformation behavior of the circular tunnel under varying lateral pressure is shown in Fig. 4. The crack propagation patterns around the tunnels under different lateral pressures are similar, and tension cracks are dominant around the tunnel, accompanied by several shear cracks. For example, the model generates 1755 and 2409 tension cracks, accompanied by 421 and 546 shear cracks, respectively, under lateral pressure coefficients of 0.5 and 1. The cracks are mainly concentrated on the surrounding rock near the tunnel surface (Fig. 4). However, the location of the failure at the roof and floor of the circular tunnel becomes more evident as the lateral pressure coefficient increases (Fig. 4). For example, a failure zone mainly appears on the sidewalls of the tunnel under a lateral pressure coefficient of 0.5, whereas a failure zone mainly concentrates on the roof and floor of the tunnel under a lateral pressure coefficient of 1.5. When the lateral pressure coefficient is 0, cracks form along the vertical direction in the surrounding rock, and the tunnel is prone to instability.

Fig. 3 (a) Generated tunnel model with a geometry of $20 \times 20 \times 7$ m. (b) simplified tunnel model with a small thickness (0.05 m) in the Y-direction.
3.3 Time-dependent response of tunnel

The time-dependent deformation of the surrounding rock continues to occur after the excavation stability. The fracture evolution as time elapses is shown in Fig. 5, in which the failure pattern of the tunnel are represented at $4.5 \times 10^2$ s, $7.5 \times 10^7$ s, and $1.4 \times 10^9$ s. The time-dependent fracture patterns are similar to those in the time-independent model (Fig. 4) under different lateral pressure. For example, cracks occur around the tunnel, and more cracks are found closer to the bottom than on the sidewalls of the circular tunnel under the lateral pressure coefficient of 1.5. Some macrocracks are formed around the tunnel, and the main failure zone is formed at the roof and floor of the tunnel for time-dependent and time-independent simulations (Fig. 5). We also observed that the failure zone around the tunnel gradually extends deeper into the surrounding rock mass as time elapses (Fig. 5).
4 Conclusions
The mechanical responses of surrounding rock of a tunnel after excavation can change with the elapsed time. In this study, we employed 3DEC-GBM to characterize the fracture evolution around a tunnel made with Yunnan sandstone at the mesoscale. The model can reproduce time-independent and -dependent fracture evolution around the tunnel. The displacements around the circular tunnel are directly related to the lateral pressure coefficients. The failure zone gradually extends deeper into the surrounding rock of the circular tunnel. The proposed 3DEC-GBM allows us to derive an in-depth understanding of the fracture evolution of the surrounding rock of a circular tunnel.

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