Digitalization and creep modelling for trinocular-cavern based metro station

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ABSTRACT: Metro stations are complex underground infrastructure encompassing wide-span caverns. Their interactions with tunnels, adits, and utilities in vicinity can have impacts on ground stability. This paper aims to undertake a novel approach leveraging digitalization of design and 3D numerical modelling to better visualize and quantify the ground-structure interaction based on a metro station featuring a trinocular cavern platform. Knowledge-based prediction is important for critical areas of underground construction. By engaging numerical modelling and using appropriate constitutive relationships for both short- and long-term deformation criteria, predictions into the ground movement and responses of ground support can be made to offer insights into the adequacy of the support system and propose monitoring scheme correspondingly, which forms an essential part of structural health management for the underground infrastructure when coupled with data-driven analytics.

Keywords: Digitalization, Long-term deformation, Numerical modelling, Trinocular-cavern, Monitoring.

1 INTRODUCTION

Knowledge-based prediction is important for critical areas of underground construction and long-term maintenance. By engaging numerical modelling and using appropriate constitutive relationships for both short- and long-term deformation criteria, predictions into the ground movement and responses of ground support can be made to offer insights into the adequacy of the support system and propose monitoring scheme correspondingly (Huang et al., 2021). With the advance in information communication technologies, a rising number of sensors and gauges are deployed to facilitate monitoring.

Numerical modelling has been engaged to investigate long-term, time-dependent deformation of tunnels (Barla et al., 2012) and underground infrastructure such as large-span caverns as part of hydropower facilities (Lee et al., 2019; Yang et al., 2014). For rock mass, literature recorded many studies using empirical approaches for identifying squeezing behavior (Aydan et al., 1996), which is described as large time-dependent convergence during tunnel excavation, as relationships are established based on rock mass quality and excavation conditions and tunnel geometry, e.g., overburden and tunnel span. Constitutive modelling of rock mass creep largely uses elasto-visco-plastic models based on general theory, particularly the overstress theory of (Perzyna, 1966) have been implemented in numerical modelling (Pellet et al., 2009), and are used to calibrate the lab-based behavior and validate parameters as well as simulating the long-term mechanical behaviors of underground construction. The comprehensive general-theory based models typically require high parameter inputs with the parameter determination process considered very time-consuming and cumbersome. Whilst the empirical and rheological creep models implemented in numerical modelling codes as built-in models require relatively less parameters and were verified for adequacy of mimicking the mechanical behaviors of rock under static load for a prolonged time and are thus easier to implement for preliminary analysis of long-term stability and support design.

Field data are mainly point-based and time-sensitive, which provides limited information about the object's status and thus insufficient to help form decisions on whether changes occurred, or interventions are required. In combination with numerical modelling, inverse analysis contributes to evaluating creep behavior and validate model parameters. This approach plays an important role in evaluating the prediction of deformation and assess structural elements, which promotes timely adaptations of support system and excavation methods based on ground response.

2 DIGITALISATION AND INTEROPERABILITY

In our previous studies (Huang et al., 2022; Huang et al., 2023), a closed-loop workflow has been established engaging heuristic techniques for exchange between building information model (BIM) and numerical model for geotechnical analysis, as shown in Figure 1. The automatic exchange of data, geometry and attributes serve the purpose of cost-effective design and validation. It also reduces the efforts of manual intervention and prevents errors due to information losses and misinterpretation. This workflow acts as a translator between the two applications before development efforts of open formats, e.g., Industry Foundation Classes, are justified by software vendors. This paper will not extend on the interoperability perspective due to the length limitation.

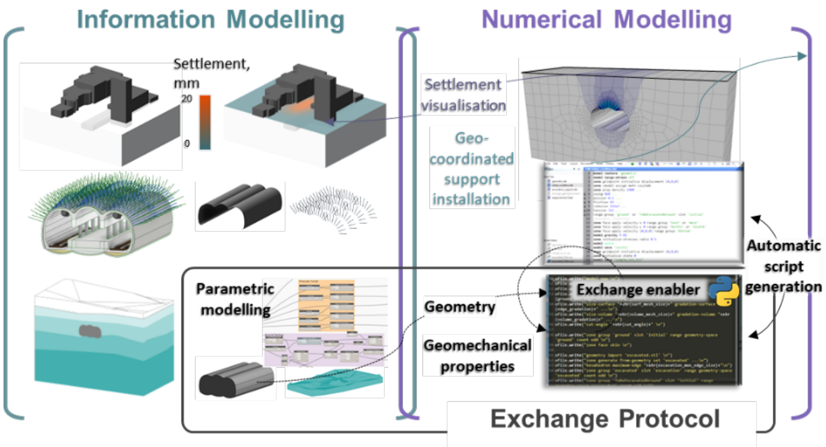


Figure 1. Framework of digitalization of design and exchange protocol for improving interoperability.

3 NUMERICAL MODELLING IN FLAC3D

The numerical model established in the numerical modelling code, FLAC3D, underpinned by FDM has a dimension of 150m × 36m × 700m, as shown in Figure 2(a). Approximately 600,000 tetrahedron meshes were generated, with the mesh size gradually decreasing from 5m at the boundary to 0.75m around the structure. The top surface is set to be free, the bottom is fixed restraining movements, and the rest of the surfaces are set to allow for normal movements. Mohr-Coulomb model is used to predict the short-term behaviors of the excavation and validate the ground support system, and Burgers model is used to predict the long-term performance.

3.1 Mohr-Coulomb model

The numerical simulation explicitly reproduced the major excavation steps taken place, they can be summarized as (1) excavation and support installation of central cavern, (2) installation of columns and other supports, (3) excavation and support installation of side caverns, (4) completed excavation. The excavation and support installation are both simulated at a 2m advance rate.

The maximum vertical displacement at the crown, as shown in Figure 2(b). Via the exchange protocol discussed in Section 2, the modelling results can be returned to the BIM model for design optimization (Figure 2c). Comparison of the maximum vertical displacement at the surface obtained by the numerical modelling and sensor result, which finds that an overestimation of settlement is produced by the simulation, this may be caused by the simplification of ground support used in the numerical model as only primary lining and rock bolts are modelled while the actual construction also engages umbrella piles especially when excavation encounters unfavorable ground conditions. However, this does not compromise the ability of the above simulation to be used as a baseline study, and to be compared with the long-term behavior of the rock mass. The column bending moment is shown in Figure 2(d).

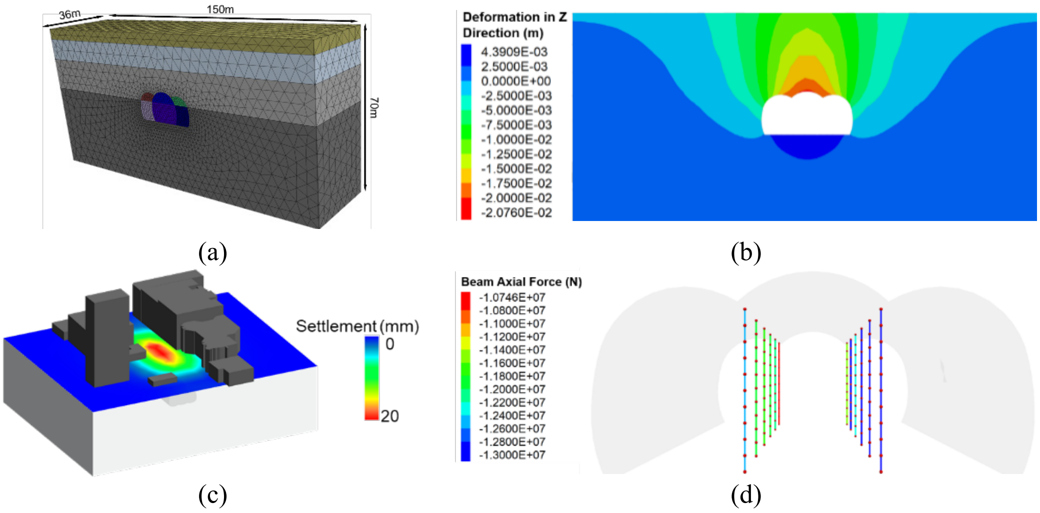
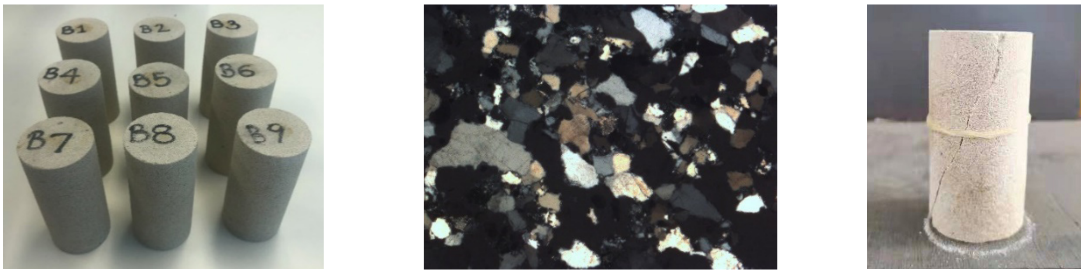


Figure 2. Mohr-Coulomb based numerical modelling for simulating station excavation and evaluates impacts.

3.2 Creep constitutive model

Silurian rocks are classical in Eastern Coast Line with a significant amount of infrastructure built in this rock group. Sedimentary rocks possess time-dependent properties. Neglecting the time-dependency of rock mass behaviors may lead to underestimation of deformations at key locations of underground structures and thus inappropriate support design (Diederichs and Kaiser, 1999; Sulem et al., 1987). However, the time-dependent properties of rock, changes of stress, strain and deformation are almost impossible to be fully captured by asset inspection and monitoring. Modelling of long-term geotechnical work provides a full-scale picture of the structure and ground interaction over time. In addition, creep behaviors are prominent only if the depth of excavation reaches a certain level. With an increasing tunnelling depth of underground projects, examples: Sydney metro (average depth 20-40m) and Opera House car park (7-42m), Melbourne Metro (20-40m) and Snowy 2.0 (approaching 1000m). The analysis should consider the varying load and stress conditions and variations of geometry. Underground stress conditions to produce time-dependent deformation can be simulated by creep tests as sustained loading and stress relaxation tests.

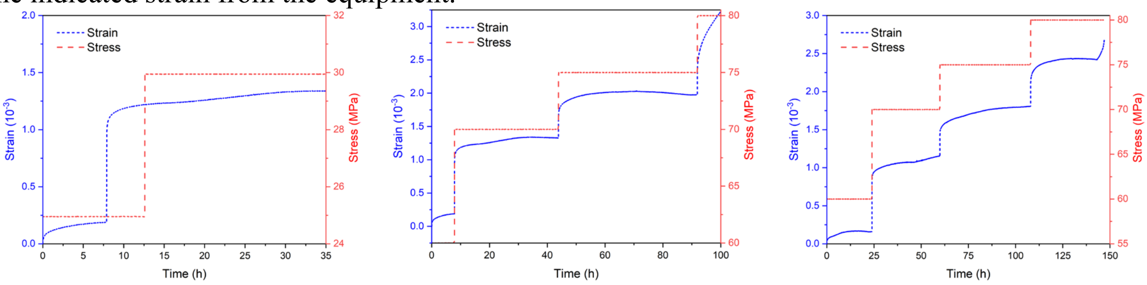
The rock specimens were prepared in accordance with the respective ISRM standards. They were cored from rock blocks and further prepared with the standard machinery (Figure a). Thin sections were taken and examined under microscopy to obtain mineralogy (Figure b). Other physical properties, including density and wave velocities, were obtained and recorded. The experiment considers short-term compressive strength and in-situ stress conditions to analyze the effect of time-varying soft rock on underground engineering. Figure (c) shows a typical sample post-failure.



(a) (b) (c)

Figure 3 (a) Cylindrical samples of Sydney Hawkesbury sandstone prepared for the tests, (b) microscopic images of thin sections of medium-grained sandstones, and (c) sample post failure.

First, the confining pressure is applied to the pre-set pressure of 1, 5 or 10 MPa through the hydraulic system, and the loading rate was 0.1 MPa/sec. Each stress level was maintained until the strain rate stabilizes at a set increasing time. Figure 4 shows time-dependent strain and loading graph at confining pressures of (a) 1, (b) 5, and (c) 10 MPa. The axial strain, and diametric strain resulting from time the uniaxial and triaxial compression creep tests can be obtained from direct reading of the indicated strain from the equipment.



(a) (b) (c)

Figure 4. Time-dependent strain and loading curves at confining pressures of (a) 1, (b) 5, and (c) 10 MPa.

Burgers rheological model is consisted of a Maxwell element in series with a Kelvin element. Burger model is described by the following evolution equation:

$$\sigma = K_M e I + 2G_M[\epsilon^D - \epsilon_M^D - \epsilon_K^D] \quad (1)$$

$$\dot{\epsilon}_K^D = \frac{1}{2\eta_K}(\sigma^D - 2G_K\epsilon_K^D) \quad (2)$$

$$\dot{\epsilon}_M^D = \frac{1}{2\eta_M}\sigma^D \quad (3)$$

where, σ^D is the deviatoric stress, ϵ^D is the deviatoric strain.

The state vector $z = (\sigma^{DT}, \epsilon_K^{DT}, \epsilon_M^{DT})$, which contains unknowns, are solved by using the Newton-Raphson method with the residual vector of

$$r_1^j = \sigma^{Dj} - 2(\epsilon^{Dj} - \epsilon_K^{Dj} - \epsilon_M^{Dj}) \quad (1)$$

$$r_2^j = \frac{\epsilon_K^{Dj} - \epsilon_K^{Dt}}{\Delta t} - \frac{1}{2\eta_K}(G_M\sigma^{Dj} - 2G_K\epsilon_K^{Dj}) \quad (2)$$

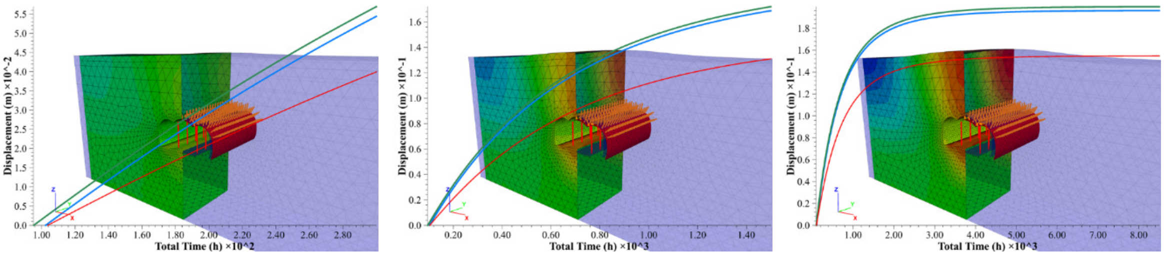
$$r_3^j = \frac{\epsilon_M^{Dj} - \epsilon_M^{Dt}}{\Delta t} - \frac{G_M}{2\eta_M}\sigma^{Dj} \quad (3)$$

Table 1 reports the derived properties determined for different confining stress levels.

Table 1. Burger model properties determined for different confining stress levels.

Confining pressures / MPa	K / GPa	G_K / GPa	η_K / MPa·h	G_M / GPa	η_M / MPa·h
1	7.417	79.943	2.642×10^4	6.035	3.307×10^6
3	7.417	324.076	2.041×10^4	10.485	1.311×10^7
5	7.417	250.364	3.225×10^4	22.681	3.559×10^7
10	7.417	351.938	1.265×10^4	16.652	2.131×10^7

Knowledge transfer from construction to operation stage, the vertical deformation vs time graph (Figure 5) at selected positions initially manifests as settlement and gradually a heaving effect at the center of the cavern is emerged. The simulation is primarily conducted to illustrate that geomaterials manifest time-dependent behavior. In addition, the creep model has not been calibrated considering the scale effect from lab-tests to actual project scale simulation. Nevertheless, the simulation indicates that for infrastructures that typically have a service life of more 100 years, it is important to consider establishing a geomechanical knowledge-based dataset or a database for the long-term structural health and functionality monitoring.



(a) (b) (c)

Figure 5. Displacement over time in multiple points (1m into the surrounding rock, middle of the crown, and near arch connection).

3.3 Predictive Maintenance Physics-based Model Database

Figure 6 illustrates the database framework incorporating both physics-based and monitoring-based data accession, links key stages of data acquisition, transfer, visualization and management, and technologies of sensing, numerical modelling, information exchange and augmentation, and querying to downstream risk management and development of warning system for predictive maintenance.

4 CONCLUSIONS

This paper aims to establish a predictive and forward-looking underground structural resilience assessment model. The scheme of achieving the model considers the failure mode of sedimentary rock structure, the different confining pressures corresponding to excavation environments with different burial depths, and the application scenarios of the model. A series of triaxial creep tests on Hawkesbury Sandstone under different confining conditions are performed. Numerical simulations of both the brittle behavior and the creep behavior of the sandstone hosting a trinocular station cavern are performed and analyzed. By interacting with BIM, a database prototype for the serviceability of long-lifetime critical underground infrastructure is proposed.

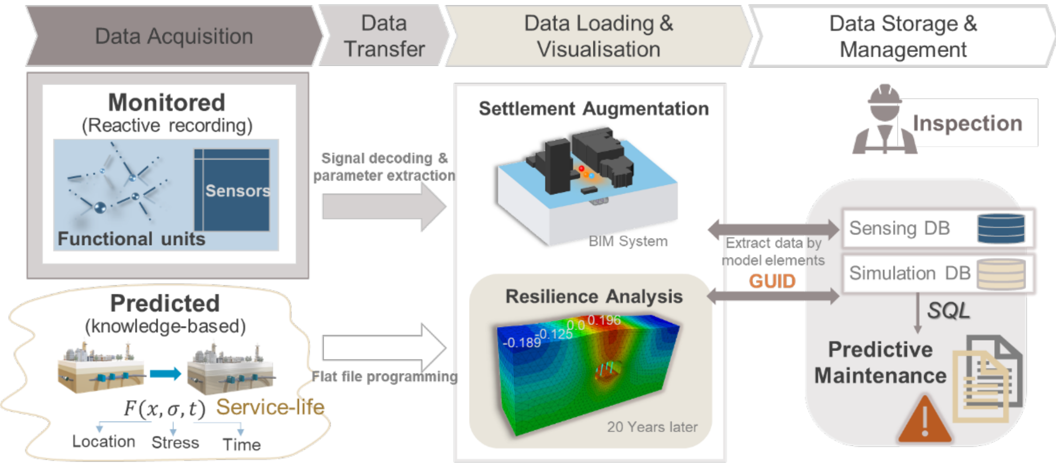


Figure 6. The Framework of Geomechanics-Knowledge Database interacting with BIM.

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