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A 3D Numerical Modelling Case Study in a Complex Granitic Rock Mass

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Abstract: The study analyses the excavation of a repository chamber in a radioactive waste storage facility in Hungary, using three-dimensional numerical modelling to assess tunnel deformations. The project's comprehensive field mapping and monitoring system made it possible to compare the results of numerical calculations based on field and laboratory measurements with the real behaviour of the tunnel. During excavation, tunnel displacements were continuously recorded using extensometers and two types of convergence measurements, which allowed a comparison of the deformations of the real and modelled environment. The displacements between the measuring points defined in the model during the convergence measurement were investigated. A mechanically realistic but simple 3D model was developed, based on extensive field and laboratory data, which reproduced tunnel displacements of the same order of magnitude as observed in monitoring measurements.

Keywords: tunnel deformation; granite; extensometers; convergence measurements; 3D numerical modelling

1. Introduction

Tunnelling in fractured rock masses presents a complex geomechanical challenge due to the heterogeneous and anisotropic nature of the subsurface environment. Accurate prediction of rock deformation during tunnel excavation is essential for ensuring construction safety, optimising support design, and decreasing project costs. 3D numerical models provide a comprehensive framework for simulating the interaction between tunnel structures and the surrounding geological media, especially if appropriate field observations and monitoring data are available.

The construction phases of a tunnel are particularly critical, as the excavation process alters the in-situ stress field and initiates time-dependent deformations. Capturing these transient effects requires advanced numerical techniques and an accurate representation of fracture mechanics and rock mass behaviour at various scales. These models facilitate predictive analysis of deformation zones, potential failure mechanisms, and support system performance under realistic geological conditions.

At the Hungarian National Radioactive Waste Repository (NRWR), repository chambers are excavated within the Mórágy Metagranite Complex, where dense fracture networks and aplite veins complicate prediction. The present study develops a mechanically realistic yet deliberately simple homogeneous 3-D model of chamber I-K3 and compares calculated displacements with in-situ measurements from extensometers and convergence sections acquired during construction. The objective is to assess how far a homogeneous model can reproduce the order of magnitude and trends of monitored deformations at the chamber scale, and to identify the principal sources of mismatch that should guide model refinement.

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2. Geology

The models tend to characterise the mechanical behaviour of a repository chamber construction in the Hungarian National Radioactive Waste Repository (Fig. 1), approximately 280 m below the surface. The host rock of the repository is the Carboniferous Mórágy Metagranite Complex.

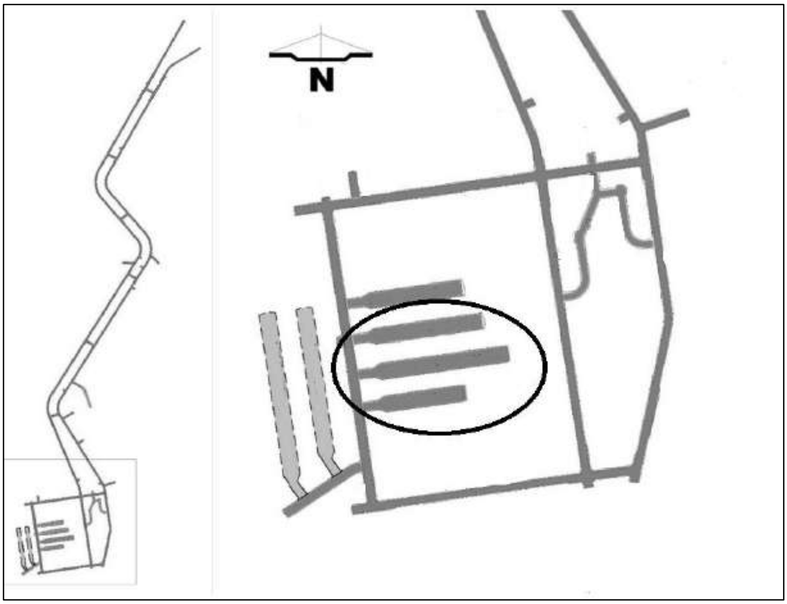

Fig. 1. Location map of the studied repository chambers.

Based on extensive empirical observations, the evolution of rock quality - and, consequently, the anticipated geotechnical conditions - within the Mórágy Granite is predominantly governed by fractures and fracture networks that developed during its tectonic evolution.

Surface and underground geological investigations have delineated six principal paleo-stress fields, within which a wide array of fracture orientations and generations have been identified. Under these distinct stress regimes, the pre-existing fracture systems exhibit varying degrees and modes of deformation, reactivation, and subsequent evolution. (Maros et al., 2003, 2009)

As a result, a complex and dense network of fracture zones and cracks has developed, characterised by significant heterogeneity in dimensions, orientations, and infilling materials. The spatial trajectories of individual fractures are generally irregular, and their terminations are frequently unpredictable due to the overprinting effects of multiple tectonic events.

The investigations further revealed that fracture infill materials cannot be uniquely associated with specific deformation phases delineated by the orientation of paleo-stress fields. In addition to discrete fractures, particular attention is warranted - from geotechnical and hydrogeological perspectives - for the more extensive fractured zones, which locally attain thicknesses of 10 meters. These zones are typically infilled with clay minerals. (Maros et al., 2009)

Findings from the early stages of the research already indicated that the geological and tectonic history of the Mórágy Formation has resulted in pronounced inhomogeneity in rock mechanical and geotechnical parameters. Consequently, the spatial extrapolation of these parameters across the site is subject to considerable limitations. (Kovács et al., 2016)

The surroundings of the survey section were overlain by monzogranite and ridge-bedded with several aplite dykes.

3. Methodology

The methodology of this study integrates field data collection and advanced three-dimensional numerical modelling to evaluate the influence of construction stages on tunnel deformation in a granitic rock mass. During excavation, deformation was continuously monitored through a network of extensometers and convergence gauges. (Krupa et al., 2015; Zierkelbach et al., 2016) Measurement sections were established along the I-K3 tunnel alignment, with specific anchor locations identified within the model domain (Fig. 2). These observational datasets were used to calibrate and validate the numerical models.

Fig. 2. A typical rock mass condition in the top heading of the repository chambers.

Numerical modelling was carried out using the RS3 software suite developed by Rocscience, which supports 3D finite element analysis. A simple homogeneous rock mass model was constructed due to the dense fracture network, representing the continuum approach without explicit fractures.

Tunnel heading advancement, excavation stages, and support installation were simulated in the RS3 environment. Displacement predictions were extracted at locations corresponding to monitoring instruments, allowing direct comparison between modelled and observed deformation patterns.

3.1. Input parameters

The numerical model adopted several simplifications that were validated and checked later in the workflow. A single chamber was modelled because the pillars between the chambers are sufficiently thick relative to the tunnel dimensions. The tunnel has a curved horseshoe profile with a crown radius of 6.4 m, overall height of 10.6 m, sidewall radius of 11.4 m, invert width of 11.08 m, and an invert dish depth of 0.91 m. To ensure that the analysed ±20 m section was not affected by end effects, a 60 m long tunnel segment was modelled. Excavation advances were 2 m for the top heading, while the bench was excavated in 4 m advances with a 20 m lag.

The rock mass was represented using the Generalized Hoek–Brown failure criterion with plastic behaviour. Table 1 summarises the adopted median properties of the monzogranite rock mass, which is the result of the statistical evaluation of approximately 600 laboratory tests. The support system consisted of 200 mm of reinforced shotcrete and 4 m-long rock bolts. The heading was additionally supported with steel lattice girders at 2 m spacing. The in-situ stress field was assumed to be constant: 8,725 kPa perpendicular to the tunnel axis, 7,261 kPa parallel to the axis, and 6,870 kPa vertically, derived from theoretical calculations and confirmed by in situ stress measurements. (Kovács et al., 2016).

Table 1. Median values of the monzogranite rock mass parameters.

GSI [-]	mi [-]	γ [kN/m^3]	UCS [MPa]	Ei [GPa]	μ [-]
42	14.4	27.06	133.1	68.07	0.235

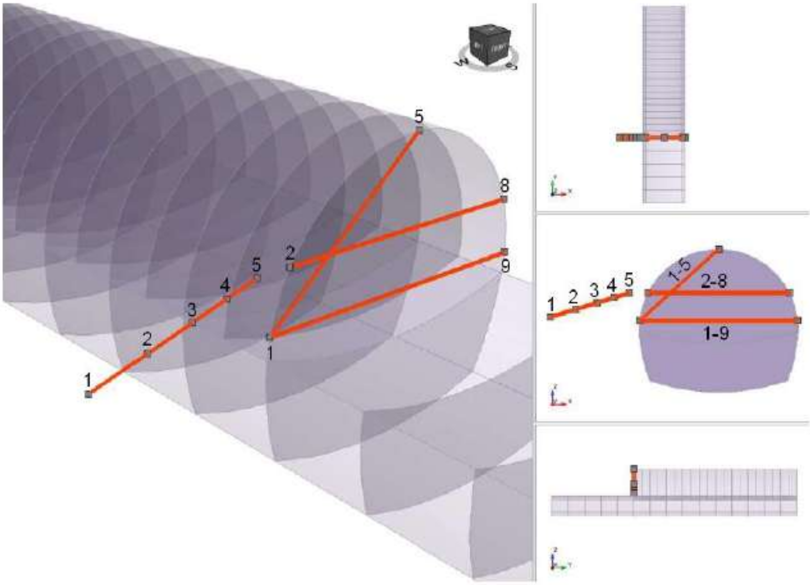

Fig. 3. Measuring sections in the RS3 model. The convergence section is inside the tunnel (1-5,2-8, 1-9), while the extensometer (1, 2, 3, 4, 5) is located outside the tunnel.

4. Results

4.1. Comparison of the displacements of the extensometer and the numerical model

Figure 4 illustrates how the calculated displacements of the modelled anchors of the extensometer varied as a function of the distance between the measurement section and the current top heading excavation face of the chamber. It can be observed that displacements remain relatively small over the first 20 m while the top heading face has not yet reached the measurement section. Once the top heading face reaches the measurement section, larger displacements are recorded at anchors 3–5, closest to the tunnel excavation. The excavation process has less effect on the displacements of anchors 1–2. The maximum displacement is shown by anchor 5, the one closest to the tunnel cross-section; its peak value, when the measurement section and the current top heading face are 20 m apart, is 0.38 mm.

The magnitude of the model's displacements is of the same order as those from on-site measurements (Fig. 5); however, their progression is slightly different. The differences can be explained by the model interpreting the surrounding rock mass as a homogeneous body, disregarding possible tectonic variations, faults, or veins.

The geology of the area surrounding the I-K3 chamber shows that cracks and aplite veins are present in the rock mass, along with displacements that could have occurred due to the excavation. In addition, the model's excavation stages are uniform, whereas the blasting depths vary slightly on-site. Due to the excavation technology, inequalities in the cross-section can easily develop, while in the model, this remains constant.

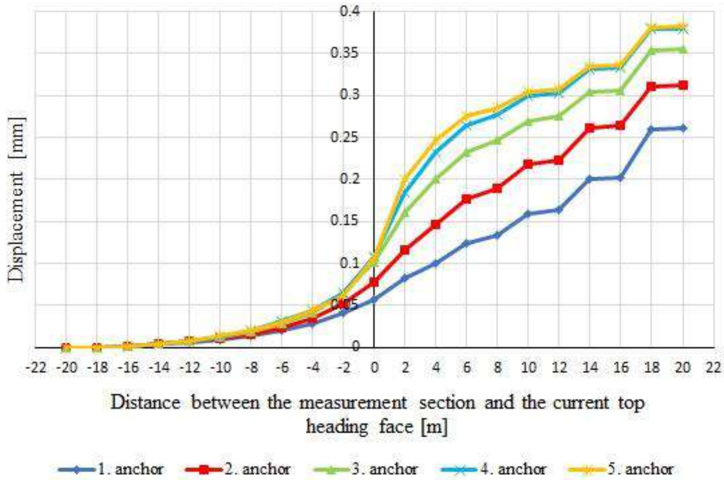

Fig. 4. Development of calculated displacements of extensometer anchors in the model as a function of the distance between the measurement section and the current top heading excavation face of I-K3.

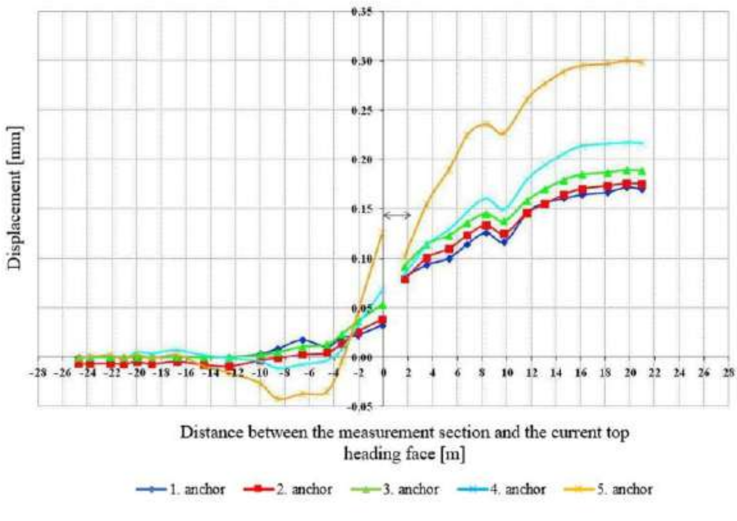

Fig. 5. Development of measured displacements of extensometer anchors as a function of the distance between the measurement section and the current top heading excavation face of I-K3.

4.2. Comparison of the measured and calculated convergence

During the mechanical convergence monitoring, the time history of tunnel lining deformation—resulting from excavation-induced changes in the stress state—was determined, tracking the successive excavation stages. Using the model's monitoring points, horizontal convergence was computed along the 1–9 and 2–8 lines, while an inclined (oblique) convergence was calculated along the 1–5 line. Figure 6 shows how the deformation between the measured points evolves regarding the convergence value as a function of the distance between the measurement section and the current top heading excavation face of I-K3. In the case of the five repeated measurements, the displacements increase uniformly in all cases. The maximum measured displacement is in the 2–8 direction (1.45 mm), while the 1–9 direction is slightly lower (1.36 mm). The smallest displacement is seen in the 1–5 direction, with a maximum value of 0.51 mm.

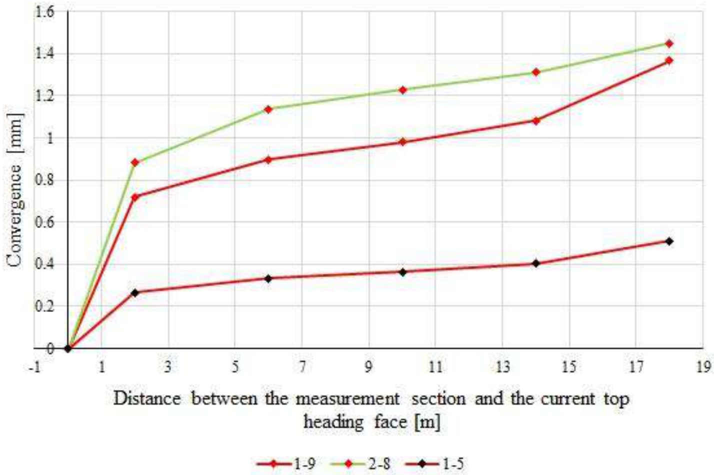

Fig. 6. Development of convergence values calculated between model-defined measurement points as a function of the distance between the measurement section and the current top heading excavation face of I-K3.

The measured values consistently show similar magnitudes and trends across repeated tests. The maximum measured displacement in the 1-9 direction is approximately 1.45 mm, in the 1-5 direction, 1.9 mm, but their order has changed. In the 2–8 direction, the measured convergence is -0.2 mm, which does not match the calculated result either in magnitude or direction. The trend also breaks down in the case of repeated measurements. During the evaluation of the convergence section's measurement results, it was noted that measuring point 8 is moving away from the tunnel axis. (Zierkelbach-Kovács, Kovács and Kiss, 2016.)

Overall, it can be said that the model did not consistently reproduce the convergence values from on-site measurements, which can be explained by the fact that the rock environment in the model is homogeneous and does not consider tectonic irregularities (presence of faults and veins). Therefore, the model results (Fig. 7) show only symmetric displacements along the tunnel lining.

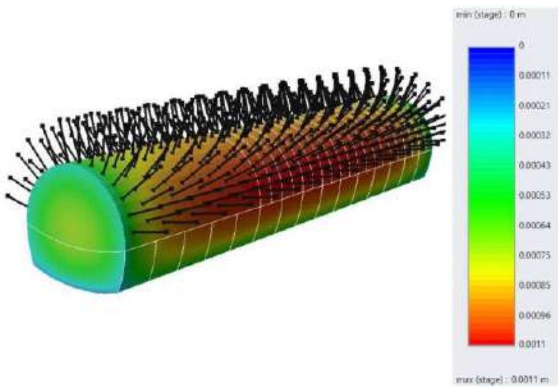

Fig. 7. Total displacements in the RS3 model.

5. Conclusion

The presented 3D numerical case study of chamber I-K3 shows that a homogeneous Generalized Hoek–Brown model, calibrated from field and laboratory data and analysed with staged excavation and support, reproduces the same order of magnitude of displacements observed on site, both for extensometer anchors and convergence measurements. Extensometer results also captured the increase in displacement as the top-heading face approached the measurement section, with the anchor closest to the tunnel cross-section showing the most significant response.

The model-predicted peak convergences of approximately 1.145 mm (2–8), 1.366 mm (1–9), and 0.511 mm (1–5) were comparable in magnitude to the measured maxima of 1.45 mm (1–9) and 1.9 mm (1–5). However, the model failed to consistently reproduce the directional trends and observed asymmetries. While the numerical simulation predicted a uniform and nearly symmetrical increase in displacement around the lining, the field data exhibited a clear direction-dependent behaviour, including negative convergence in the 2–8 direction and localised deformation peaks.

The most plausible explanations for these discrepancies are the homogeneous rock-mass assumption, which overlooks key tectonic heterogeneities such as faults, fracture corridors, and aplite veins, and the associated stiffness and strength anisotropy. Additionally, the model's simplification of construction realities, such as variations in blast rounds and minor deviations in the excavation profile, likely contributed to the differences between the predicted and observed behaviour.

Implications for design and analysis. A homogeneous equivalent-continuum can be adequate for first-order magnitude checks and preliminary support sizing for fractured granites, provided it is confronted with monitoring data. Still, it is insufficient to reliably capture directionality and localisation of deformations. This aligns with wider experience that monitoring (convergence and extensometers) is essential to validate and update predictions during construction.

Recommendations for future modelling:

- Introduce heterogeneity (mapped fracture corridors/aplite veins as reduced-stiffness/strength volumes) or adopt a DFN-informed equivalent to better capture anisotropy and asymmetric convergence. (Li and Elmo, 2024)
- Reflect construction nuances by varying the lengths of the advances and face shapes in the staging, and by including realistic support-installation lags.

The study demonstrates that a simple, homogeneous 3-D model is a useful baseline and decision aid. Still, it should be augmented—guided by monitoring—to incorporate site-specific heterogeneity if directional behaviour and localisation are critical to support verification at the chamber scale.

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