Experimental and numerical study on the creep behavior of a rock mass with filled joints

Maximiliano R. Vergara
Skava consulting SA, Providencia, Chile
Skava consulting ZT, Salzburg, Austria
Institute of Soil Mechanics and Rock Mechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany

Ana Libreros
Ed. Züblin AG, Zentrale Technik - Tunnel Engineering, Stuttgart, Germany

Karl Balthasar
Institute of Soil Mechanics and Rock Mechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany

ABSTRACT: The time-dependent behavior of the rock mass is primarily controlled by the time-dependent deformation of the rock mass discontinuities. While most investigations concerning creep in rock masses have focused on the creep behavior of the intact rock, there is limited experimental data available on the creep behavior of rock fractures and discontinuities. In this study, direct shear creep tests were carried out on rough and saw-cut rock joints artificially filled with ground rock to investigate the creep behavior of rock fractures in the laboratory. The experimental results demonstrate that the creep deformation and failure potential in a filled joint depends on the shear-stress/shear-strength ratio, the magnitude of the shear stress, and filling thickness. Subsequently, the observed creep behavior of the rock joints was implemented into a numerical model to simulate the creep response of a jointed rock mass with varying fracture densities.

Keywords: Rock joint creep, Rock mass creep, Joint shear creep test, Rock mass creep model.

1 INTRODUCTION

The knowledge of time-dependent behavior is crucial for the long-term stability of structures excavated in rock masses, such as slopes, mines, caverns, and waste repositories (Bieniawski 1970). Creep deformations can cause block instability, alterations in excavation geometry, sliding of rock slopes and increased rock mass permeability (Wang 1981; Larson & Wade 2001; Glamheden & Hökmark 2010)

The deformation of rock masses is strongly influenced by the presence of discontinuities, including bedding planes, faults, and joints, and the same applies to creep deformation. However, creep in rock discontinuities is still not well understood, and there is a lack of experimental work to accurately describe and represent this phenomenon.

Experimental investigations into the time-dependent deformation of rock masses have largely focused on the behavior of intact rock, leaving a gap in our understanding of the creep behavior of rock fractures. To address this gap, the present study examines the creep behavior of rock joints through direct shear creep tests performed on filled rock joints. These tests were conducted on both rough and saw-cut joints under varying loads and infill thicknesses.

2 EXPERIMENTAL WORK

2.1 Specimen preparation and testing apparatus

The test specimens consisted of two sandstone blocks with a joint filling made of ground claystone. Two types of fractures were tested: saw-cut and rough joints. The rough joints were created by splitting the rock specimen along its long axis using a press, producing tensile failure. The sandstone blocks were then encapsulated using high-strength plaster to fit them into the shear apparatus, as shown in Figure 1.

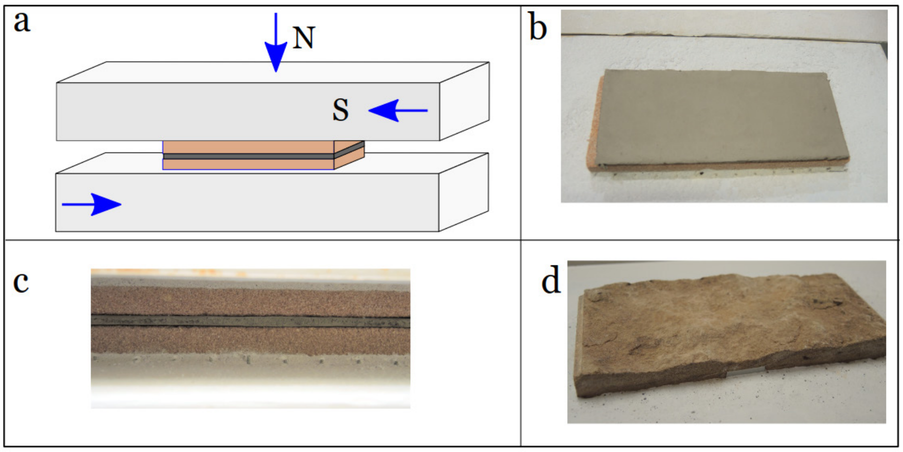

Figure 1. a) Direct shear test configuration. N and S: normal and shear loads respectively. b) Clay filling sheet on saw-cut joint. c) Detail of filled joint. d) Rough joint JRC=8.

To prepare the joint filling, the claystone was sieved to a size of < 0.25 mm, mixed with water and formed into sheets of varying thicknesses using a press. These sheets were left to dry for several days at 30 °C to minimize cracking, reaching a final water content of about 3%. The joint area, and hence the sheet area, was approximately between 100 and 120 cm^2.

The test device used in the tests was a servo-controlled hydraulic direct shear apparatus with a maximum shearing area of 300 x 150 mm, maximum normal and shear forces of 500 kN, and a maximum shear displacement of 90 mm.

2.2 Testing method

After preparation of the specimen, a conventional direct shear test was performed. The direct shear tests were carried out under constant normal load (N) at a speed of 0.5 mm/min. The tests showed a peak strength at approximately 1 mm deformation before reaching the residual shear strength. The peak can be attributed to the cohesion formed by the preparation of the filling clay sheet. Upon testing the specimen for the second time, the peak strength was not observed, and a similar residual strength was reached. The same trend occurred for further test on the same specimen.

To eliminate the virgin state of the specimen and to achieve good reproducibility between tests, a direct shear test was performed on the fresh claystone filling before conducting the creep tests. The residual strength value obtained from the direct shear test was used to select the loads for the creep tests.

The direct shear creep tests were conducted under constant normal and shear load, with horizontal and vertical deformations being recorded. The normal load varied between 22 and 80 kN, resulting in normal stresses of 2 to 8 MPa for the given specimen size. The shear load was selected based on a specified stress level, which was determined as the ratio of the applied shear stress to the shear strength (τ/τ_s).

3 EXPERIMENTAL RESULTS

3.1 Effect of the shear stress level

Shear creep tests were conducted under stress levels between 0.7 and 0.9. As previously observed in investigations by Höwing & Kutter (1985) and Malan et al. (1998), stress levels lower than 0.7 do not exhibit significant creep behavior.

Figure 2a displays the results of a creep test on a single specimen with increasing shear stress under a normal load of 80 kN. The filling thickness is 3mm. The results exhibit a transient primary creep stage followed by a linear secondary creep stage. Higher stress levels result in greater deformation during the primary stage, followed by a higher deformation rate in the secondary stage.

3.2 Effect of absolute magnitude of shear stress

To test the effect of the stress magnitude on creep behavior, different tests were performed on the same specimen at a shear stress/strength ratio of τ/τ_s = 0.9, varying the normal load. The results, presented in Figure 2b, show that for the same stress level, the creep behavior also depends on the stress magnitude. The higher the stress (for the same stress level), the higher the deformation rate during primary (transient) and secondary (steady state) creep stages.

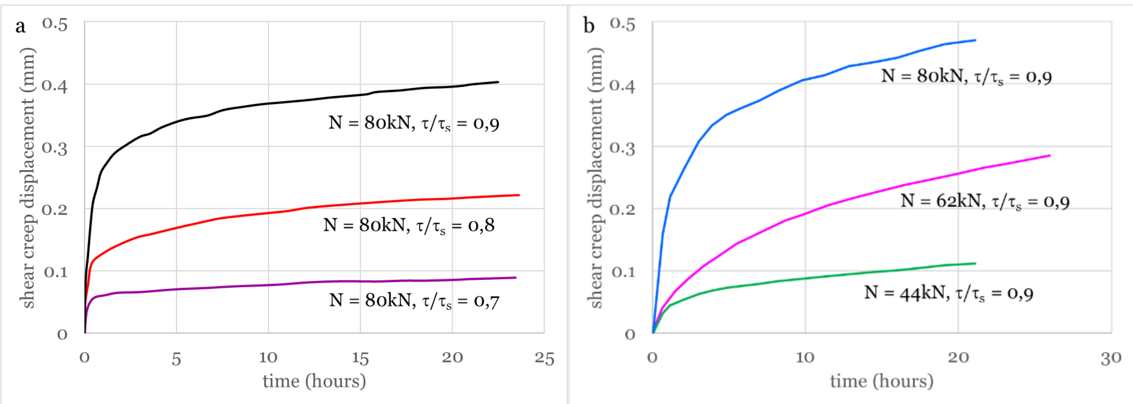

Figure 2. Results of shear creep tests on a saw- cut rock joint with 3mm infilling. a) Different shear stress level (τ/τ_s) under constant normal load (N). b) Constant stress level (τ/τ_s) under different normal loads (N).

3.3 Effect of infilling thickness

The effect of infilling thickness was studied by conducting shear creep tests under constant normal load and shear stress level on specimens with varying filling thickness. The joint friction angle, determined in the conventional direct shear tests, varied between 23° and 33°, which was considered for the calculation of the shear stress level. The results displayed in Figure 3a show the effect of infilling thickness on creep behavior, where a higher infilling thickness resulted in higher deformation during the first creep stage and a higher creep rate during the second creep stage.

3.4 Effect joint roughness

The effect of joint roughness was also studied by conducting shear creep tests under constant normal load, with varying stress levels, on joints with a roughness coefficient JRC of about 8. Figure 3b shows the results of the test on an infilling of 1.5 mm. The creep displacement occurred at a low rate compared to that of saw-cut joints and was only significant at a high shear stress level (τ/τ_s =0.9).

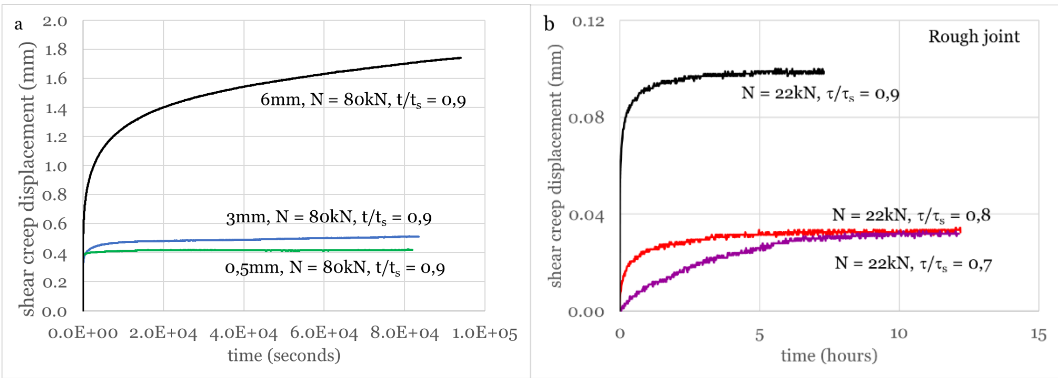

Figure 3. Results of shear creep tests. a) Saw-cut joint with different infilling thickness at constant stress level (τ/τ_s) and constant normal load (N). b) Rough joint with 1,5mm infilling at constant normal load (N) and increasing stress level.

4 NUMERICAL MODELLING

Based on the experimental results, a numerical model was used to study the creep behavior of a rock mass containing filled discontinuities.

4.1 Model description

A finite-element model was created using the software ABAQUS. The model consisted of a 2 x 2 x 2 m cube intersected by planes. The geometry was generated using a MATLAB code that exported it as a python script to be read in ABAQUS. The intact rock was modeled with solid elements while the discontinuities (filled joints) were modeled using cohesive elements, which are available in the ABAQUS library (Vergara et al. 2020). The mechanical behavior of the materials was controlled through a user-defined subroutine (UMAT). A uniaxial creep test was simulated under a constant load of 1 to 10 MN applied over one year.

4.2 Discontinuity network and fracture density

The orientation of the discontinuity sets considered in the model and the resulting model geometry are presented in Figure 4.

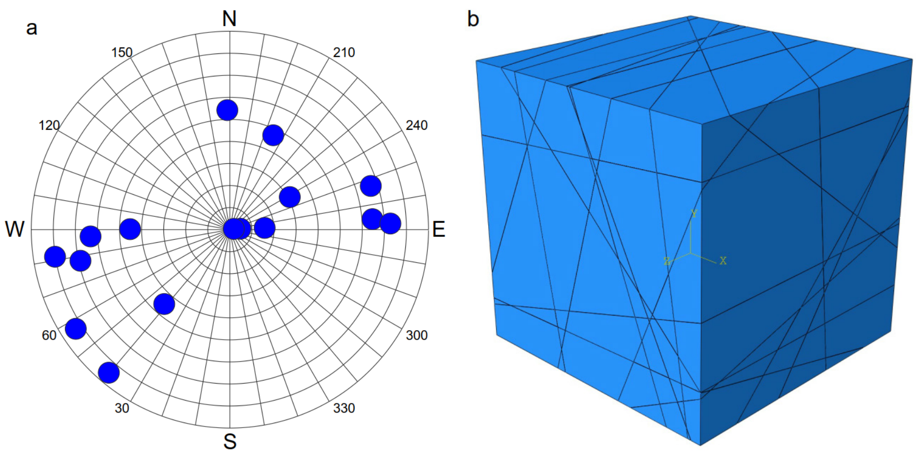

Figure 4. a) Pole plot of the orientation of the discontinuities included in the model (16 planes). b) Model geometry in ABAQUS (2 x 2 x 2 m).

Three rock volumes with different fracture densities were modeled to compare their creep behavior and observe the influence of the joints. To generate models with lower fracture density, some of the planes shown in Figure 4 were removed from the initial fracture network.

Rock mass models containing 8, 11 and 16 planes were generated. The volumetric discontinuity density (P_{32}), calculated as the ratio between total fracture area and rock mass volume, in these models are 3.9 m^2/m^3, 5.2 m^2/m^3 and 8.0 m^2/m^3 respectively.

4.3 Material properties

The shear creep behavior of the joints was modeled using a rheological model. A Burgers material with viscous and elastic constants η_1, η_2, E_1, and E_2 was implemented in the UMAT to control the shear behavior of the joint elements (Figure 5):

$$\sigma + \left(\frac{\eta_1}{E_1} + \frac{\eta_2}{E_1} + \frac{\eta_2}{E_2}\right)\dot{\sigma} + \frac{\eta_1}{E_1}\frac{\eta_2}{E_2}\ddot{\sigma} = \eta_2\dot{\varepsilon} + \frac{\eta_1\eta_2}{E_1}\ddot{\varepsilon} \quad (1)$$

The shear creep displacement calculated for a shear surface of 200 mm length using two parameter sets simulating slower and faster creep, is illustrated in Figure 5.

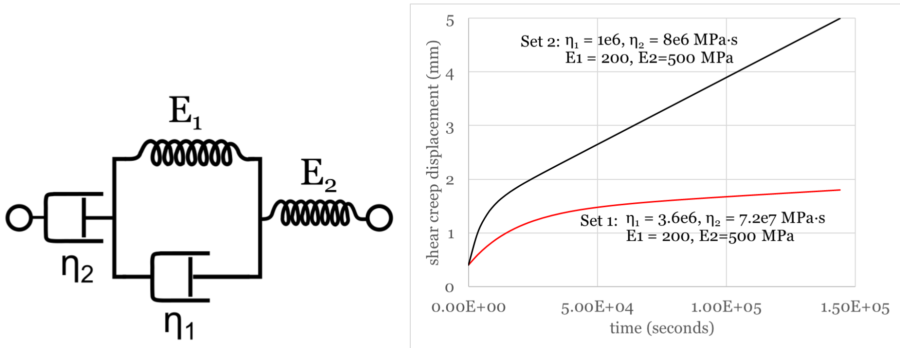

Figure 5. Schematic diagram of Burgers model and calculated shear creep displacement on a 200 mm-length joint for two different parameter sets.

The values of Burgers model parameters used in the simulations of the uniaxial creep tests were selected based on the experimental data. However, the model has been simplified, and the influence of the absolute stress magnitude on the creep behavior has not been taken into account.

The intact rock was modeled as linear elastic because significant failure is not expected under the low stress levels and low deformation anticipated during the creep test simulation. A Young's modulus of 10 GPa and a Poisson's ratio of 0.25 were assumed for the intact rock.

4.4 Results of uniaxial creep test on jointed rock mass

The results of the simulations are presented in Figure 6. It is observed that the creep deformation is proportional to the load and fracture density. This can be attributed to a higher fracture density enabling greater relative displacements between blocks. On the other hand, lower fracture density promotes interlocking of blocks, hindering the creep displacement. This can explain the behavior of the model containing 8 joints, which shows almost no difference in creep deformation when the faster creep parameters are used (Figure 6a).

The creep deformation of the models with 11 and 16 joints increased by a similar amount when the faster creep parameters were used. This means that there is a certain degree of independence from fracture density. This can be attributed to the fact that deformation and sliding primarily occur along specific joints, and the presence of additional discontinuities may not significantly modify this behavior. Similarly, the higher vertical load has a strong influence on the creep of the model with 11 joints, while the model with 8 joints shows no significant effect from the higher load (Figure 6b). This difference can be attributed to the interlocking of the intact rock blocks within the model.

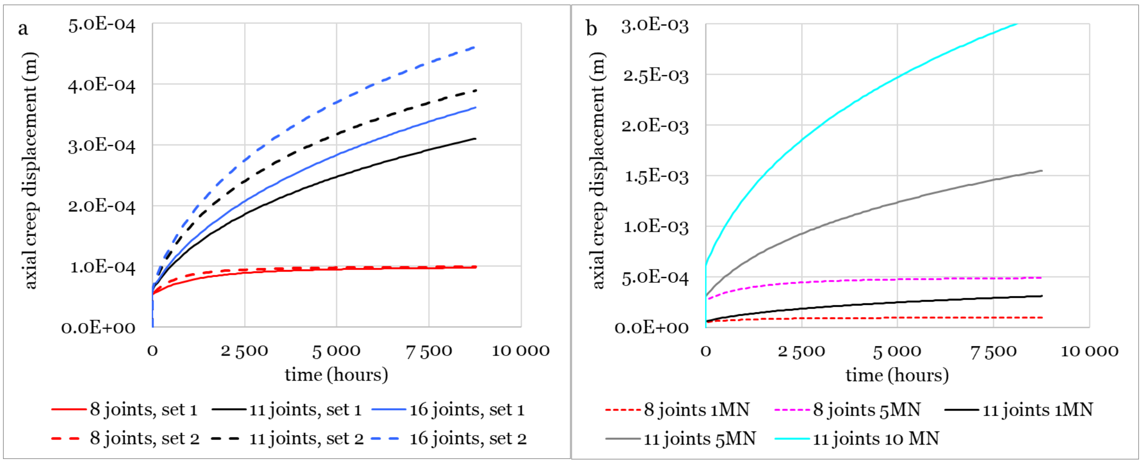

Figure 6. Results of uniaxial creep test on jointed rock mass. The parameter sets refer to those to simulate slow (set 1) and fast (set 2) creep, shown in Figure 5. b) Uniaxial creep test under different vertical loads.

5 CONCLUSIONS

The creep behavior of rock fractures was investigated in the laboratory through direct shear creep tests conducted on rough and saw-cut joints that were artificially filled with ground rock. The experimental results show that the creep deformation and failure potential of a filled joint depend on the shear-stress/shear-strength ratio, the absolute magnitude of the shear stress, and the thickness of the filling material.

The creep behavior of the rock joints was implemented into a numerical model to simulate the creep behavior of a jointed rock mass with varying qualities, determined by the fracture density. The results of the simulations indicate that the creep deformation is proportional to the load and the fracture density. Higher fracture density allows greater relative displacements between blocks, resulting in enhanced creep behavior. Conversely, lower fracture density promotes interlocking, which hinders creep displacement. Overall, the results suggest that understanding the creep behavior of rock joints is essential for predicting the long-term performance of jointed rock masses.

REFERENCES

Bieniawski, Z.T. 1970. Time-dependent behaviour of fractured rock. *Rock mechanics*, *2*(3), 123-137.

Glamheden, R., & Hökmark, H. 2010. Creep in jointed rock masses. State of knowledge. *Report R-06-94,* Svensk Kärnbränslehantering AB. Retrieved from https://www.skb.com/publication/2184298

Howing, K.D., & Kutter, H.K. 1985. Time-dependent shear deformation of filled rock joints – a keynote lecturer. In: *Proc. Int. Symp. Fundamentals of Rock Joints*, Bochum, Germany, September 15, 1985, pp. 113-122

Larson, M.K., & Wade, R.G. 2001. Creep along weak planes in roof and how it affects stability. *Transactions Society for Mining Metallurgy and Exploration Incorporated 310*, pp. 47-54.

Malan, D.F., Drescher, K., & Vogler, U.W. 1998. Shear creep of discontinuities in hard rock surrounding deep excavations. In: *Mechanics of jointed and faulted rock: proceedings of the third International Conference on Mechanics of Jointed and Faulted Rock–MJFR-3,* Vienna, Austria, pp. *6-9.*

Vergara, M.R., Arismendy, A., Libreros, A., & Brzovic, A. 2020. Numerical investigation into strength and deformability of veined rock mass. *International Journal of Rock Mechanics and Mining Sciences 135*, 104510. DOI: 10.1016/j.ijrmms.2020.104510

Wang, S. 1981. On the mechanism and process of slope deformation in an open pit mine. *Rock mechanics*, *13*(3), 145-156.