Assessment of the creep behavior of siltstone for the Snowy 2.0 hydropower station using multistage uniaxial and triaxial creep tests

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Content

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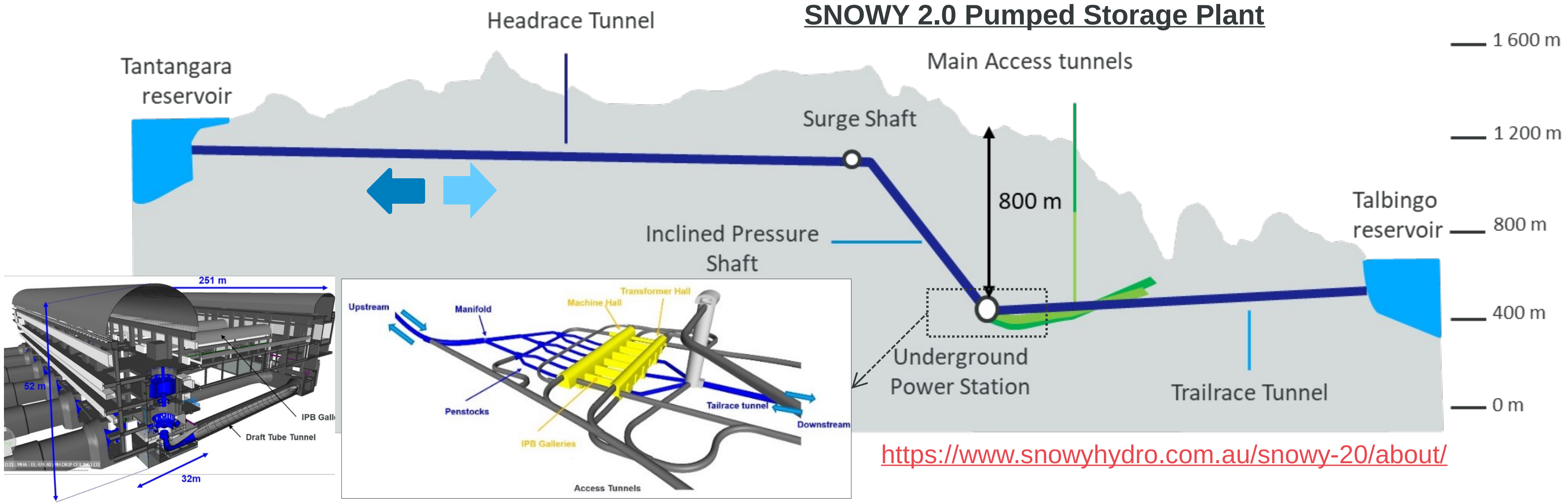
Introduction

- The effects of time-dependent behaviour of rocks (creep) should be considered while planning underground construction projects, especially in sedimentary rocks such as “Siltstones” :
  - For rock support and steel liner design
  - Load transfer consideration to adjacent structure
  - Space proofing requirements
- Understanding the time-dependent behavior of rocks involves conducting rock creep tests over time periods lasting weeks or months :
  - Primary creep
  - Secondary creep
  - Tertiary creep

Description of the Snowy 2.0 project

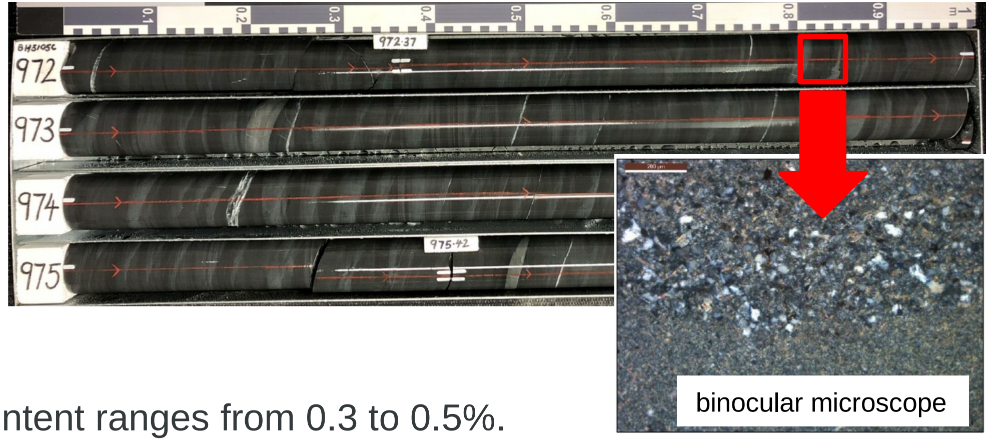
- One of the largest underground pumped storage projects in the world and Australia's largest ongoing renewable energy project – 2 000 MW (6 reversible Francis units)
- 2 caverns at 800m depth: Machine Hall and Transformer Hall: with L 251 x H 52 x W 32m - and L 223 x H 50 x W 20m, respectively.



https://www.snowyhydro.com.au/snowy-20/about/

Geology and lithology at the project site

- The two caverns and surrounding underground structures are comprised within one main geological formation (*Ravine Beds* - Shallow marine shelf deposits - Silurian period - 443,8 to 419,2 My).
- **Interlaminated to interbedded siltstone/sandstone** (with siltstone representing 70 to 85% of the layers).
- The beddings vary from dark grey (finer textures – argillaceous beds) to light grey (coarser textures – arenaceous beds).
- UCS from 50 to 100 MPa.
- RQD 90-100%.
- Porosity is low (0.5 to 1.5%) and water content ranges from 0.3 to 0.5%.



binocular microscope

Creep testing and sample preparation

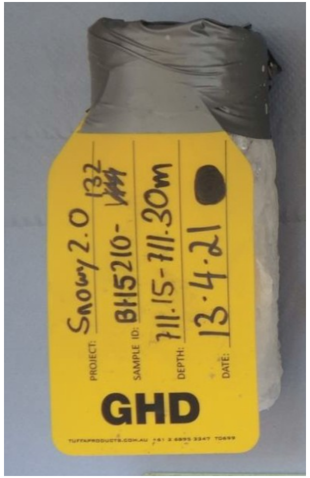
Testing procedure and sample preparation

- The study is based on 71 UCS tests, 183 conventional triaxial tests, 15 uniaxial creep tests and 5 triaxial creep tests
- Testing standard: ASTM D7070-16
- Specimens Diameter: 40 mm; Length/Diameter ratio: 2

Table 1. The list of samples used for triaxial creep tests and triaxial tests on samples from cavern depth.

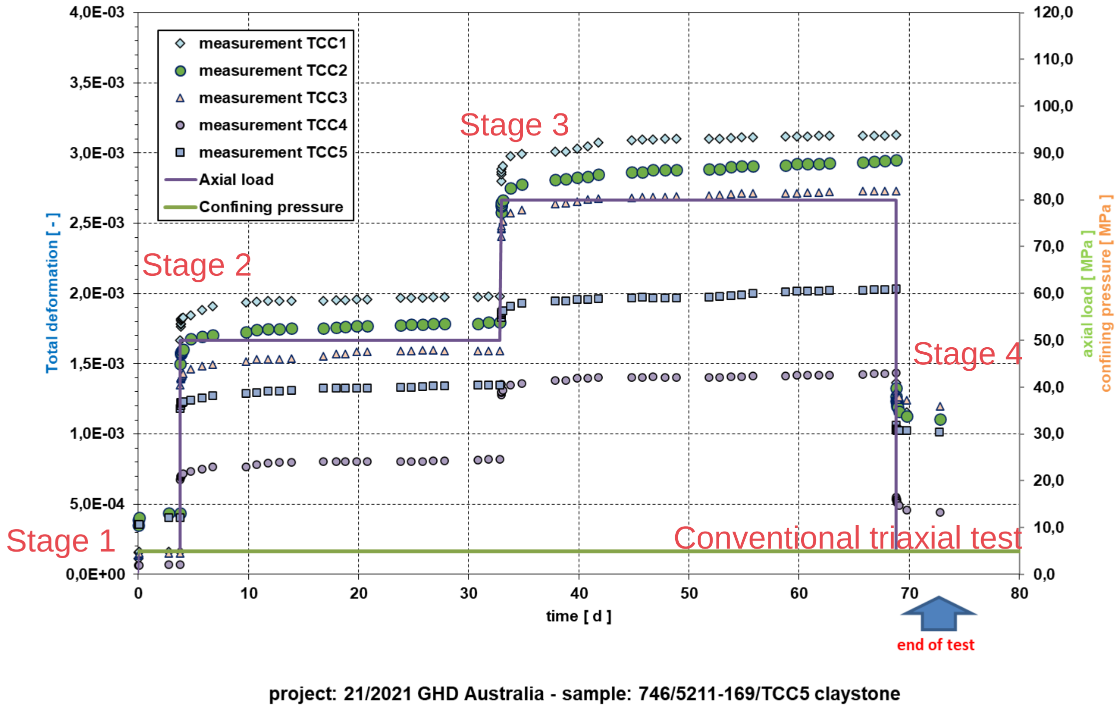
Tests name	Extraction depth (m)	Lithology SLT/SST	Nb. of test stages	Test duration (days)	Failure stress [(1)] (MPa)
TCC1 & TC1	711.15	90%/10%	4	73	111
TCC2 & TC2	786.85	70%/30%	4	73	114
TCC3 & TC3	791.00	80%/20%	4	73	121
TCC4 & TC4	835.00	70%/30%	4	73	171
TCC5 & TC5	867.85	80%/20%	4	73	143

Waxed



IfG lab (2022)

Testing procedure and sample preparation



IfG lab (2022)

- Mechanical, weight-controlled machine
- constant temperature and humidity
- 0.001 mm accuracy of the measured deformations
- 4 testing stages :
  - **Confining stage :** 5 MPa
  - **Axial loading stage :** 50 MPa then 80 MPa for 4 weeks each
  - ***Axial Unloading stage***
- Conventional triaxial test was conduct at the end

Experimental results

Short-term strength and deformation

- 71 UCS and 183 conventional triaxial tests were performed on neighboring samples to :
  - Determine the stress levels to be applied on samples during the creep tests.
  - Compare the short-term results to the long-term ones.
- The rock becomes stronger, tougher, and stiffer at higher confining pressures

Table 2. Short-term mechanical uniaxial and triaxial parameters for siltstone samples.

n	σ_3 (MPa)	$\overline{\sigma_p}$ (MPa)	$\overline{\varepsilon_p}$ (10^{-6})	$\overline{\text{E}}$ (GPa)
71	0	70	-	44
36	2	91	1908	50
36	5	109	2283	51
42	10	122	2613	52
39	20	157	3235	54
30	40	227	4566	56

Long-term strength and deformation

Recall of uniaxial creep test

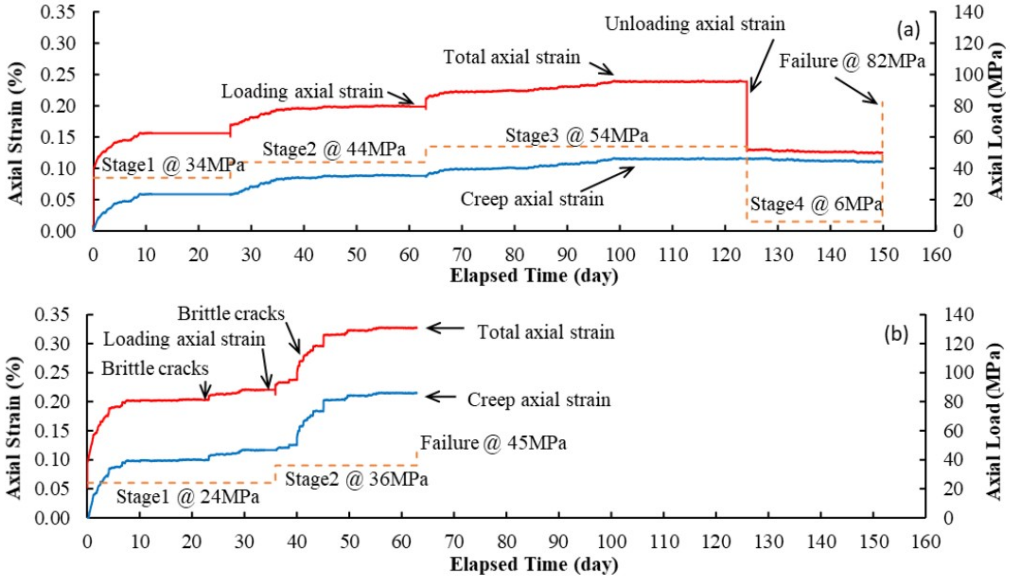


Figure 4. (a) Uniaxial creep result of test n.11, Group 1; (b) Uniaxial creep result of test n.9, Group 2.

S Abou Kheir *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1124** 012003

- Recall of the longest uniaxial creep tests :
  - Primary creep has been **observed with 0,1% of creep strain and 30% reduction of modulus**
  - Secondary creep has **not been observed**
  - Tertiary creep for high **stress/UCS** ratio with **brittle deformations**

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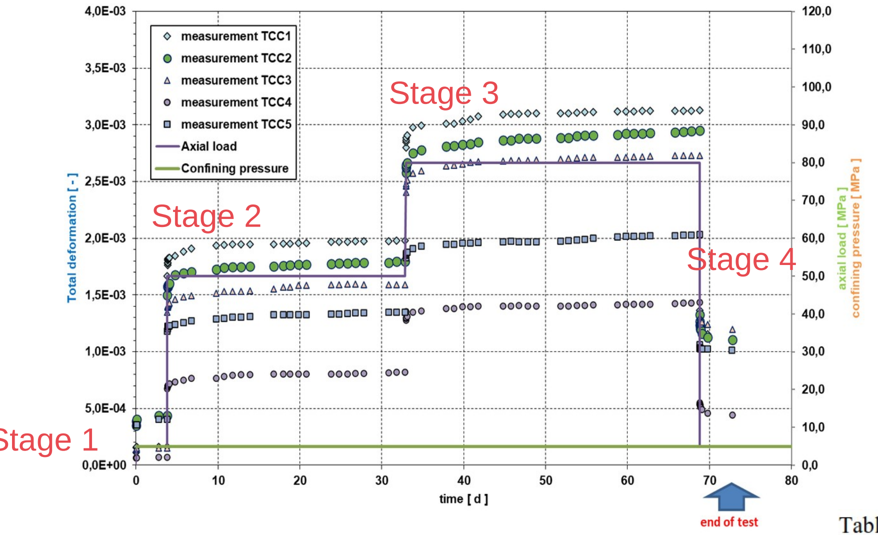
Long-term strength and deformation
Triaxial creep test



project: 21/2021 GHD Australia - sample: 746/5211-169/TCC5 claystone

IfG lab (2022)

- 50 MPa / 132 MPa of average compressive strength vs 109 MPa from the initial conventional triaxial tests.
- Occurrence of a primary creep: 0.014% to 0.035%.
- Creep strain rates at end of tests: 0.63 με/d and 3.27 με/d
- An instantaneous modulus Ei of 48 GPa compared to the short-term modulus of elasticity of 51 GPa.
- An apparent modulus ET of 39 GPa. (18% reduction)
- **Unloading stage**

Table 3. Summary of triaxial creep test results for siltstone samples with 45 MPa differential stress.

Test name	σ_3 (MPa)	σ_1 | σ_p | Ratio (MPa)	Duration (days)	ε_c (x 10-6)	E_i (GPa)	E_T (GPa)	$(E_i - E_T) / E_i$ (%)
TCC1	5	50 | 111 | 45%	29	312	30	25	17%
TCC2	5	50 | 114 | 43%	29	295	42	33	22%
TCC3	5	50 | 121 | 41%	29	245	38	31	17%
TCC4	5	50 | 171 | 29%	29	141	74	60	19%
TCC5	5	50 | 143 | 34%	29	162	58	48	17%
Average values		50 | 132 | 38%	29	231	48	39	18%

Long-term strength and deformation
Triaxial creep test VS uniaxial creep test

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1) Primary creep investigation

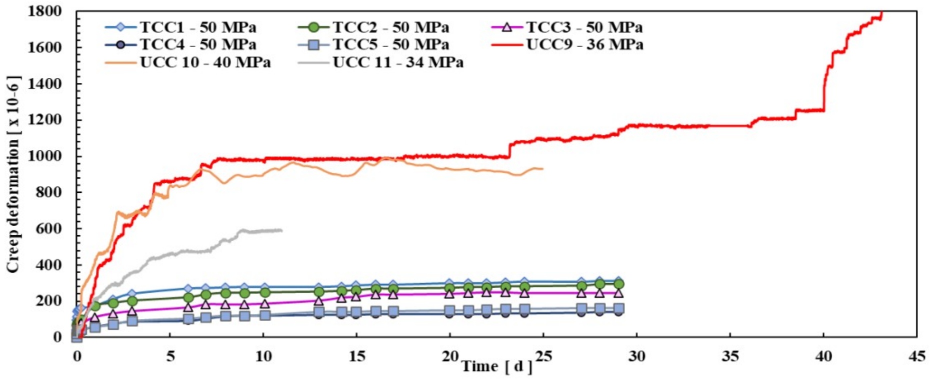

Figure 3. Comparison between 5 triaxial creep tests with 45 MPa differential stress and uniaxial creep tests from Abou Kheir et al. (2023). UCC: uniaxial compressive creep test. TCC: triaxial compressive creep test.

- The uniaxial creep have **higher deformation amplitudes** than the triaxial creep.
- The 5 MPa confinement of the triaxial tests **reduces the creep amplitude**.
- The creep at the end of the triaxial tests is equivalent to a reduction of Ei of 18% compared to 30% from the uniaxial creep tests.

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Long-term strength and deformation
Triaxial creep test VS uniaxial creep test

2) Secondary creep investigation

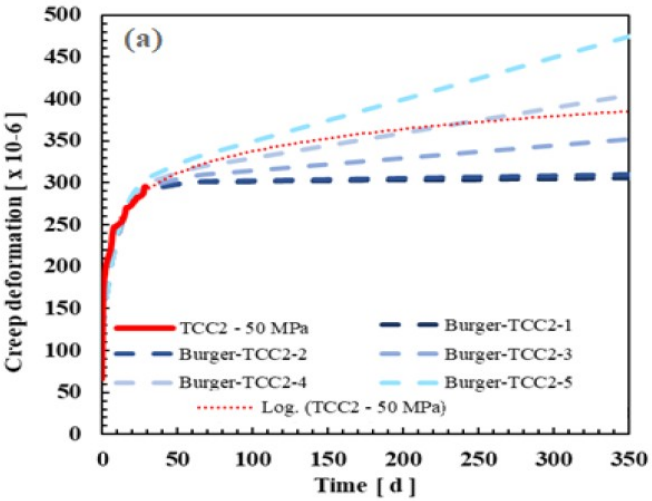

Figure 4. Comparison between (a) the empirical logarithmic curve and multiple rheological Burgers fits to TCC2 triaxial creep tests - all with $R^2 > 0.9$; and (b) the empirical logarithmic curves and Burgers fits to axial strain creep of each of the TCC triaxial creep tests. All the curves have an $R^2 > 0.9$.

Logarithmic empirical and Burgers model for **TCC2** triaxial creep test :

- The logarithmic model (2 variables) **simpler** but tends to **overpredict** long term strains based on shorter test durations.
- The Burgers model (4 variables) **more flexible**, mechanistically sound, and can provide better fit to the data, resulting in a **more constrained long-term prediction. But for a good fit** the secondary creep phase should be well represented in the test duration.

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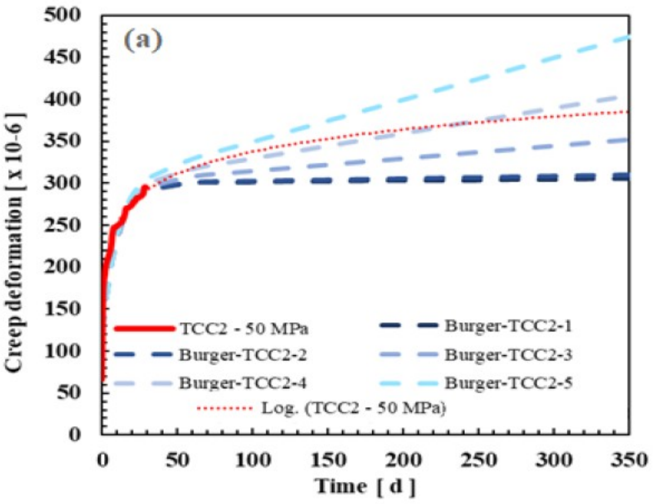
Long-term strength and deformation
Triaxial creep test VS uniaxial creep test

2) Secondary creep investigation



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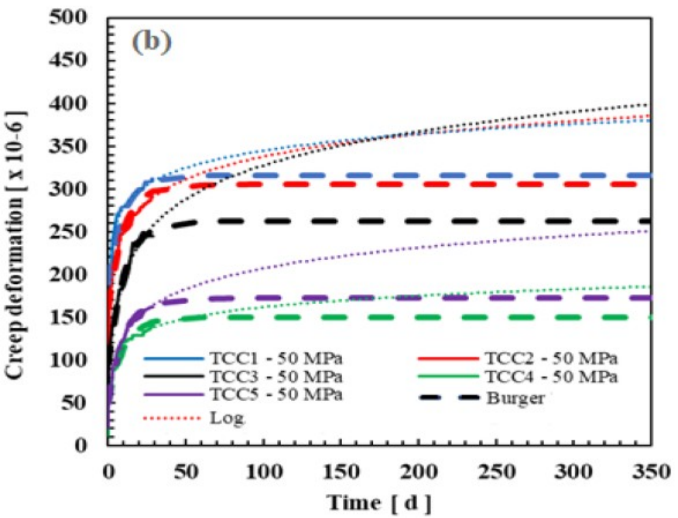
Logarithmic empirical and Burgers model for **TCC2** triaxial creep test :

- the R2 of the Burgers model is insensitive to a slight modification of its parameters but presents significant change in its extrapolation prediction
- It is advised for future creep tests to load the samples up to a duration until a steady creep stage is well evidenced i.e. **where the steady state represents more than half of the recorded creep data**

Long-term strength and deformation
Triaxial creep test VS uniaxial creep test

2) Secondary creep investigation



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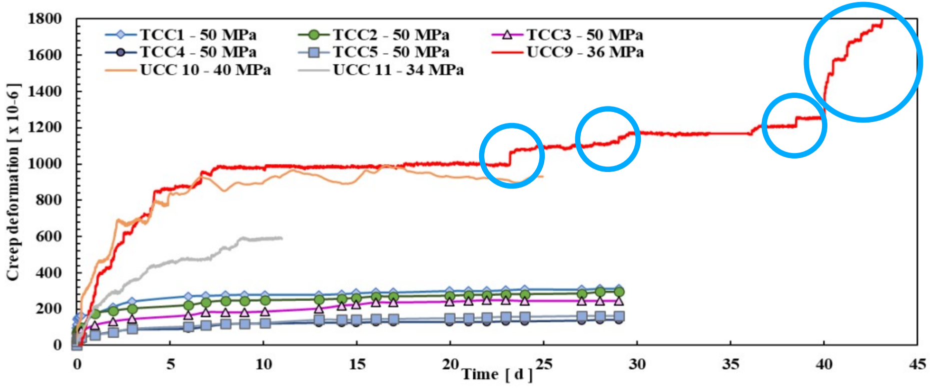
- Based on :
    - Very **low porosity** of 0.5 to 1.5% few spaces to a secondary creep to happen.
    - Secondary creep not observed from the uniaxial creep tests
- It was judged that the creep stain rates of the triaxial tests to be in a continuous decrease and that a secondary creep is not adequate.

Long-term strength and deformation
Triaxial creep test VS uniaxial creep test

3) Tertiary creep investigation



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5 of 15 uniaxial creep tests brittlely deformed:

- The tertiary creep of uniaxial creep test number 9 is presented with brittle deformations.
- The triaxial creep tests didn’t exhibit any brittle deformation.
- It is estimated that the confining pressure in the triaxial tests inhibits any brittle deformation of intact siltstone.

Conclusions

Final conclusion

- The time-dependent behavior of Siltstone was influenced by various factors**: including confining pressure, ratio of axial stress to compressive strength, and loading duration**, and presented different responses between **loading and unloading stages**.
- Occurrence of a primary creep.
- Secondary creep has **not been observed** at the time scale of the creep tests – 3 months. The risk of existence of a secondary creep is unlikely (not measurable) because siltstone has a high density close to the theoretical maximum density.
- Considering the influence of the confining pressure on creep, it is recommended that future investigations mainly use triaxial creep tests as they better capture the in-situ stress regime.

Final conclusion

- For modeling purposes, the characteristic modulus for Siltstone is **decreased by 30%** to account for the primary creep during the excavation of the caverns.
- A logarithmic empirical model tends to overestimate any forecasted creep strains
- The rheological Burgers model is more flexible and can provide better fit to the data:
    - though it has more parameters and requires sufficient duration of data for adequate accuracy.
    - It is advised for future creep tests to load the samples up to a duration until a steady creep stage is well evidenced. **more than half of the total recorded creep data.**

References

- Abou Kheir, S., Bamford, B., Brogiato, A., De Carli, G. & Lambrughi, A. 2023. Assessment of the creep behaviour of siltstone for the Snowy 2.0 hydropower. IOP Conf. Ser.: Earth Environ. Sci. 1124 012003.
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