Time-dependency and long-term strength of rocks in brittle underground environments – from the lab results to numerical continuum analysis

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ABSTRACT: There has been a wide effort to develop constitutive models to aid prudent engineers or scientists in understanding materials' behaviour in rock mechanics. Hoewever, there is still a lot of work to be done when considering time-dependent behaviour that can lead to instabilities and progressive failures which cannot be captures when considered the commonly used constitutive models, usually static. This paper aims to provide more insight into understanding time-dependent behaviour at both the laboratory and excavation scale. Building on the findings this study develops in-depth understanding on capturing the time-dependent behaviour in brittle rock materials proposing a new approach to be adopted when simulating numerically this behaviour highlighting key considerations both at the laboratory and tunnel scale.

Keywords: long-term behaviour, time-dependency, time-to-failure, creep, strength degradation

1 INTRODUCTION

Underground space is increasingly considered a sustainable engineering solution accommodating the ongoing and emerging needs of human beings, from transportation and natural resources to storage needs and energy applications (Paraskevopoulou et al., 2022). An ongoing increase in infrastructure development has been observed during the last two centuries. The latter raises the concern that many such infrastructures are approaching or have exceeded their design lifetime. Figure 1 shows the average lifetime of various infrastructures based on design standards such as EUROCODE and British Standards.

The question then arises is what current engineers and scientists should do to either re-purpose these infrastructures and prolong their lifetime or optimise current design practices to accommodate such future challenges. It is evident that many underground infrastructures have exceeded their lifetime and are still in operation. Great examples are the Victorian railway tunnels in the UK (Atkinson et al., 2021) that currently need refurbishment but still planning to be in operation (Smith et al., 2023). Nevertheless, the performance of a geo-structure over time remains, making the time-dependent behaviour of host rocks for underground structures crucial today (Paraskevopoulou, 2021). Consequently, the primary aim of this paper is to give more insight into how brittle rock types perform over time in underground conditions.

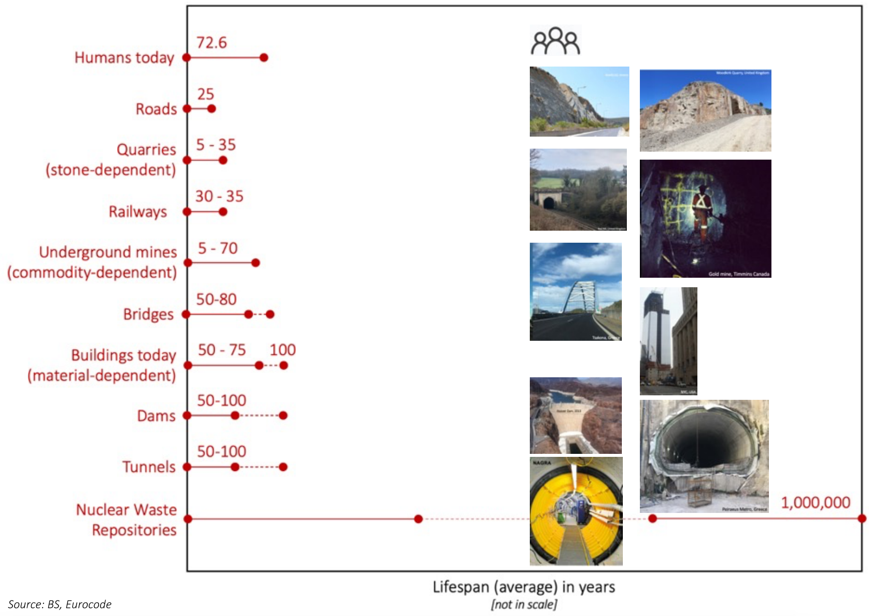


Figure 1. Average design lifespan in years of infrastructure.

2 TIME-DEPENDENT BEHAVIOUR IN ROCKS

It is known that different rock types can behave differently over time, mainly driven by their geological origins and in-situ conditions (Paraskevopoulou, 2016). Time-dependency, which refers to the deformation or property change of rock and other materials over time, has been investigated by many colleagues over the years, mainly in the past century. However, there needs to be more clarity and interpretation of the actual phenomena and their driving mechanisms, as many have noticed (Diederichs et al., 2017; Innocente et al., 2021; Paraskevopoulou, 2021). Figure 2 summarises the main time-dependent phenomena that can act individually or simultaneously when in-situ conditions favour their triggering mechanisms.

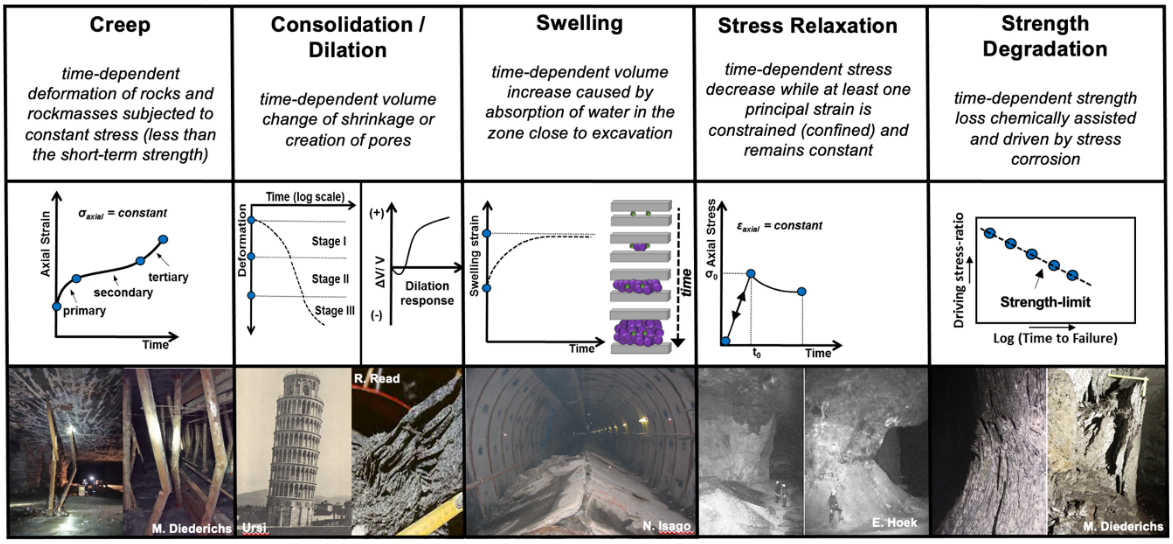


Figure 2. Examples of time-dependent phenomena, the behavioural response with time and a description of the phenomena encountered in rock tunnelling (Paraskevopoulou, 2021).

Furthermore, according to Paraskevopoulou (2016) the overall physical response can be a combination/integration of the mechanisms that influence the long-term behaviour of intact rock and rock masses and include:

- creep during which visco-elastic behaviour governs where time-dependent, inelastic strains and 'indefinite' deformation occur and/or visco-plastic yield where time-dependent plastic strains occur that lead to permanent deformation (Paraskevopoulou et al. 2018);
- dilation or contraction where volume change takes place over time usually caused by the change of stress resulting in the propagation and interaction of cracks (dilation) or the closure of the existing ones (contraction) ((Paraskevopoulou et al. 2018 and Innocente et al. 2022);
- swelling where volume increase is caused by absorption of water around the excavation zone (Paraskevopoulou, 2021);
- relaxation where the reduction of the stress with time under sustained strain is controlled by the internal creep processes aimed at relieving the stored elastic energy (Paraskevopoulou et al. 2017);
- mechanical property degradation where strength and/or stiffness change due to damage processes that accompany or occur as a result of the above phenomenon (Paraskevopoulou et al. 2018 and Innocente et al. 2021).

2.1 Time-dependency in brittle rocks

It is accepted that progressive damage that can lead to failure is primarily dominated by the initiation and propagation of microcracks in the direction of the maximum load (Diederichs et al., 2017). During axial compression, four distinct stages that lead brittle materials to failure can be identified and showing in Figure 3:

1- closure of pre-existing cracks;
2- linear elastic behaviour (reversible strains);
3- stable crack growth that is initiated by CI (Crack Initiation threshold); and i
4- unstable crack growth which is initiated by CD (Crack Damage threshold), which leads to failure and the peak strength or Uniaxial Compressive Strength (UCS), the point of maximum stress.

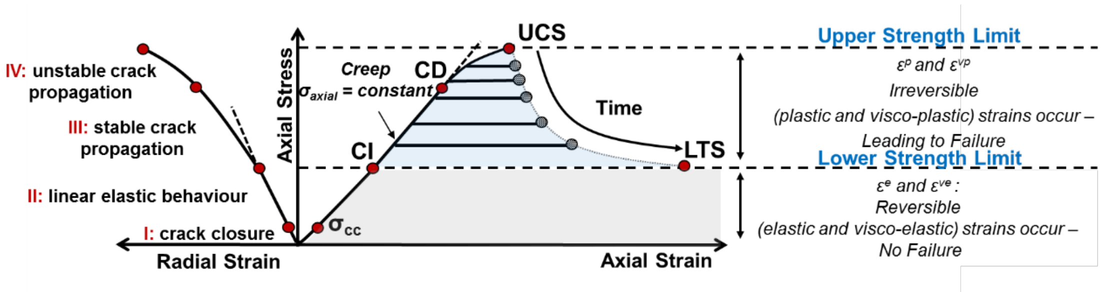


Figure 3. Stress - strain response and stages of brittle rock fracture process and evolution of the short-term strength of the material to its long-term strength when subjected to a constant stress conditions, (where: σ_{cc} – stress level at crack closure, CI – crack initiation, CD – critical damage, UCS – unconfined compressive strength, σ_c – applied constant stress) (Paraskevopoulou, et al. 2018).

The influence of time has been investigated on the Long-Term Strength (LTS) of rocks and mainly brittle materials (Figure 3) by performing static load (creep tests) in the laboratory by sustaining the axial stress (load) constant.

2.2 Long-term strength (LTS)

Long-term strength tests are commonly conducted to assess the stability of engineering projects with lifespans on the order of hundreds of years. With increasing interest in the ultra-long lifespan of underground nuclear waste repositories, understanding the long-term stability of brittle rocks is increasingly important (Innocente et al., 2021). In order to estimate the LSR involves both a series of uniaxial compressive strength tests and a series of static (load tests) to estimate the UCS (maximum strength) and then record the stress level and the time-to-failure as shown in Figure 3. Based on such results, a database can be developed for LTS degradation for various rock types from various publicly available data shown in Figure 4.a.

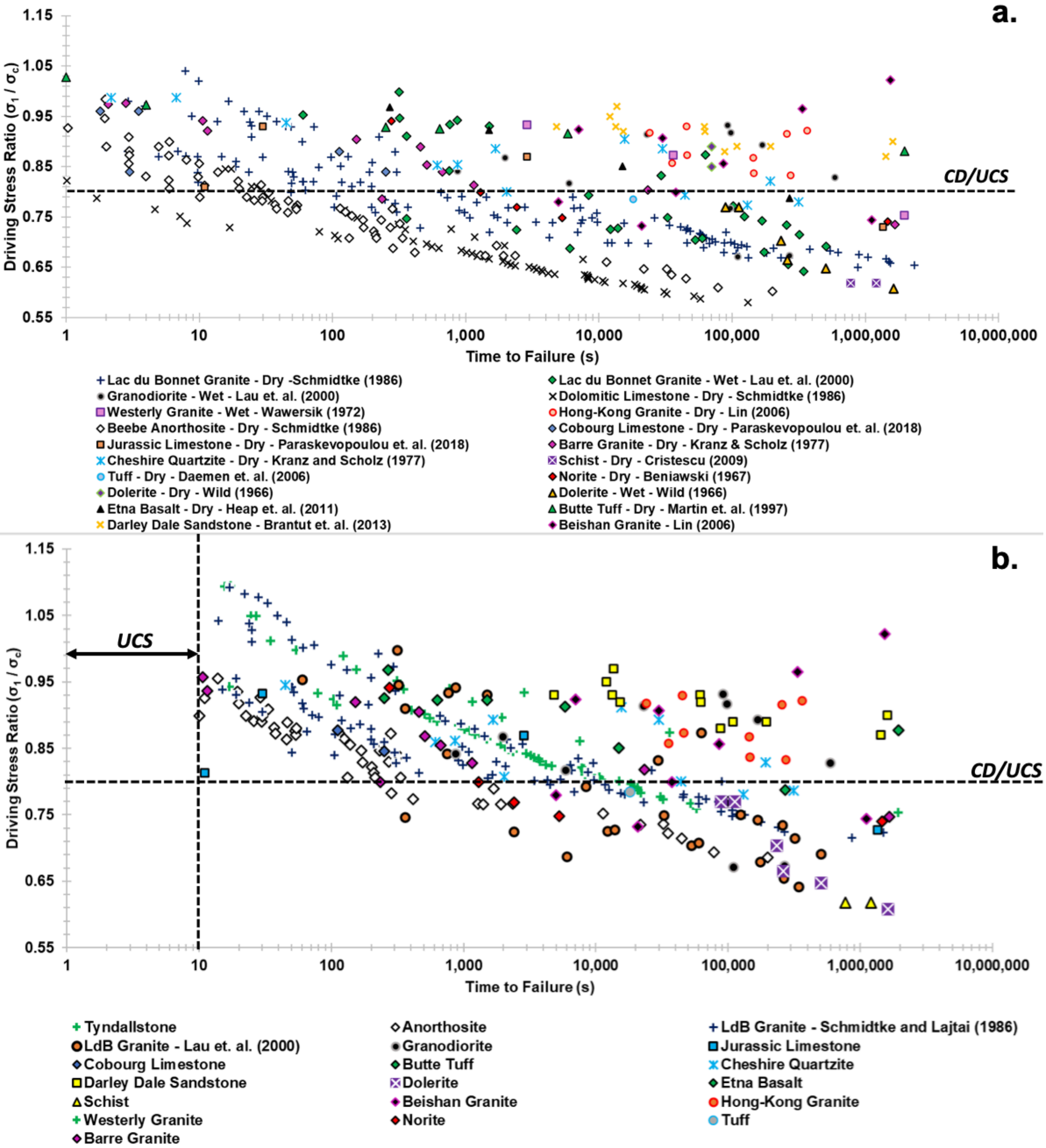


Figure 4. a) Time-to-failure tests for all rocks studied from literature, performed at relative room temperature and humidity, as well as at varying levels of saturation as noted; and, b) Long-term strength data for all rocks studied after taking the first 10 seconds as the UCS for rocks that failed within it. CI and CD thresholds have been overlain to better highlight the change in stress regimes (Innocente et al. 2021).

Paraskevopoulou et al. (2018) suggested an alternate method for determining the Driving Stress-Ratio (DSR) during a long-term test in which a similar UCS test regime is conducted prior to long-term strength testing. However, the CI and UCS thresholds are determined for each test. From these tests, an average CI/UCS ratio can be found. Since all long-term strength tests must be loaded above the CI threshold of the rock for failure to occur, as previously discussed, this ratio can be used to determine sample-specific UCS values if the sample is loaded according to the ISRM suggested methods and ASTM standards (ISRM 1983; ASTM, 2014). Innocente et al. (2021) proposed that if one is interested in the long-term strength of rock or the long-term stand-up time of excavation, they are likely not interested in the strength within the first 1 to 10 seconds of load application. In practice, one would say a rock that fails after 1 to 10 seconds failed 'instantaneously' after load application.

Figure 4.b shows the exact data for all rocks plotted on the DSR vs TTF plot after using the first 10 seconds of data as the UCS. It is clear from Figure 4.b that there is much less spread in the data, and a more apparent downward trend can be observed.

3 NUMERICAL APPROACH FOR LTS IN 2D

As discussed in Section 2, the most common method for determining the long-term strength of brittle rocks is by conducting a series of uniaxial compressive strength (UCS) tests to determine the average strength of the rock. Once the desired stress is reached, it is held, and its Time-to- Failure (TTF) is recorded and compared to the applied Driving Stress-Ratio (DSR). The modification includes degrading the strength of the criterion.

3.1 Proposed LTS model

The proposed LTS (Innocente et al., 2022) is built on the existing CVISC creep model (from ITASCA) by modifying the attached Mohr-Coulomb plastic slider. Figure 5 shows a schematic representation of the model's behaviour.

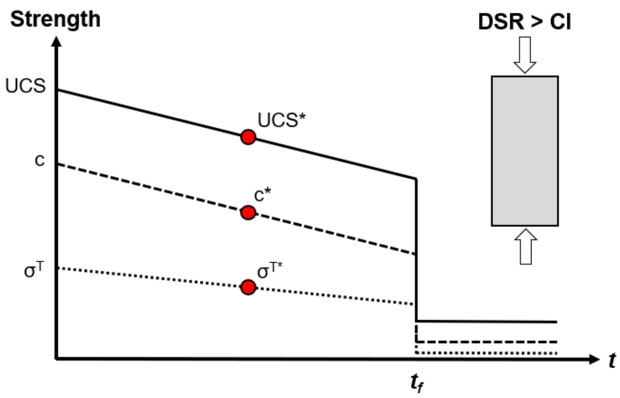
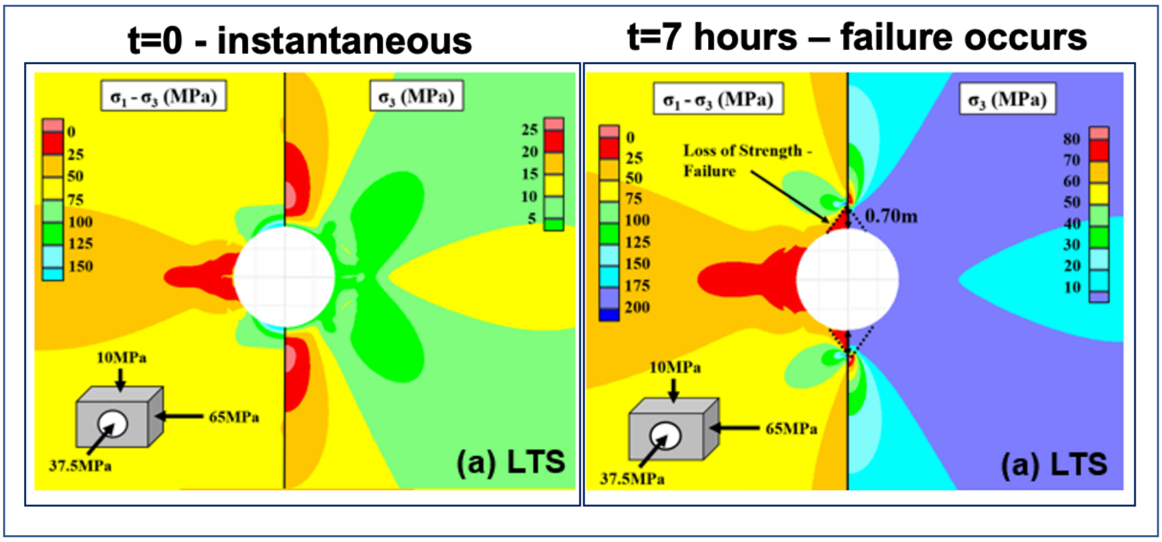


Figure 5. Schematic representation of the LTS model and the effect on the respective strength parameters when a sample is subject to an applied constant load greater than its CI threshold, Where: UCS* is the new UCS value after weakening, c* is the new cohesion after weakening, σ_i^T is the initial intact tensile strength; and, σ^{T*} is the new tensile strength after weakening, t_f is time of failure; and, t is time. Note that friction angle has been omitted as it is assumed constant until failure (Innocente et al. 2022).

Figure 6 shows the results of the proposed LTS (Innocente et al., 2022) using FLAC2D (from ITASCA) of an underground opening at instantaneous time=0 and after t=7 hours. The failure geometry is shown as a shear "cone" extending outwards from the tunnel periphery, also known as the "process zone".



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4 DISCUSSION AND CONCLUSIONS

Historically, time-dependent behaviour in brittle rocks is often interpreted from time-to-failure laboratory data where an average UCS value from earlier lab testing and regression analysis is performed on the driving stress ratio rather than a log-linear approach, as shown in Figure 4. It is shown that this approach results in a large spread of data both within the same data set and between data sets which limits its applicability. It is proposed that if during a lab test, a sample fails during the first 10 seconds of final load application, that load be taken as equivalent to the UCS of the sample and be used further to normalize the DSR for subsequent long-term strength tests. This has the consequence that the first 10 seconds of any model fit after that can not be reliably used to calculate TTF within 1 to 10 seconds. However, this is not very important for long-term analyses. In addition, it is shown that using an average UCS value for DSR calculations is inadequate due to variation in UCS between samples. Therefore, sample-specific CI values be used to calculate sample strength using average CI to UCS values. The LTS model assumes that the rock stays intact until the material ruptures throughout the damaging process. The LTS model, shown herein, has successfully been implemented into a continuum finite-difference model. The LTS model assumes that the rock stays intact until the material ruptures throughout the damaging process.

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