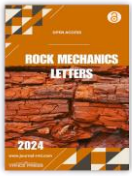
Rock Mech. Lett. **2025**, 2(1): 11

VANCE PRESS

Rock Mechanics Letters

www.journal-rml.com



Research Article

Effects of temperature, water content, hydraulic pressure, stress level and damage on rock creep and the prolonged stability of deep underground structures

Wadslin Frenelus[1,*], Hui Peng[1]

[1] *Department of Hydraulic Engineering, College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang City, 443002, China*

[*] Correspondence: wadslin@ctgu.edu.cn

Received: 24 December 2024
Revised: 23 January 2025
Accepted: 09 February 2025
Published date: 12 February 2025
Doi: 10.70425/rml.202501.11

Abstract: As multifunctional structures, deep rock underground structures are built all over the world. Their lifespan is generally expected to exceed a hundred years. However, they are inexorable to rock creep which controls their durable safety and stability. This article describes the strong factors affecting rock creep and the lasting stability of deep rock engineering, based on pertinent research works. It shows that temperature, water content, hydraulic pressure, stress level, and damage are major factors that significantly affect the creep behavior of host rocks of deep underground structures. Overall, such factors govern the creep life of rocks hosting deep underground constructions. Specifically, the increase in these factors causes an increase in the creep strain rate, a shortening of the steady creep phase, an acceleration of the onset of tertiary creep, and thus a shortening of the time-to-failure of rocks. For instance, the higher the temperature, the shorter the duration of the steady creep phase and the faster the triggering of the tertiary creep phase. Likewise, the higher the stress level, the shorter the creep process, and the faster the time-to-failure of rocks. The greater the damage extent, the weaker the surrounding rocks, and the shorter their time-to-failure. Similarly, the higher the water content, the faster the appearance of the tertiary creep stage. The highest hydraulic pressures cause the shortest rock creep process and the fastest outbreak of tertiary creep. This is due in particular to the fact that fluctuations in these factors disintegrate the internal structure of the rocks and make them increasingly weakened. As a result, the mechanical properties of the rocks are altered and the creep process proceeds at a higher rate than expected. Hence, the creep life of the surrounding rocks is reduced, which significantly limits the prolonged stability of deep underground structures. When these factors are taken into account, rock creep can be better captured and typical structural diseases like convergence deformation can be better controlled. Appropriate countermeasures, such as long-term monitoring of the rocks housing such structures, are strongly recommended.

Keywords: Rock creep; Complex rock environments; Major factors influencing rock creep; Creep constitutive models; Deep underground structures; Prolonged safety and stability; Rock creep monitoring; Structural integrity

1. Introduction

Deep underground structures are multifunctional structures that are increasingly being built around the world. In fact, they can generally perform various major functions like water conveyance, hydropower stations, sanitary drainage, irrigation, transport, mining, energy storage systems, and so forth. Ordinarily, they are expected to have a long lifespan which may even exceed a hundred years. However, owing to the complex behavior of deep rock engineering which generally face high in-situ stress, abundant groundwater and high geotemperatures [1-5], engineering issues are frequent, and most of these structures are put out of service after short operation time and require enormous repair work. This is generally due by several factors. On the one hand, depending on the rock type which preponderates the regional environment of a given underground structure, the convergence rate can be considerable as earlier than expected. Typically, after rock excavation, the structure convergence rate can be augmented for months or years and is also accompanied with gradual deterioration of rocks [6]. In such a situation, the prolonged safety and stability of the structures is threatened and can no longer be ensured, if suitable remedial measures are not taken in right time. On the other hand, development of cracks and fractures around the host rocks and in the secondary lining of such structures may be notable. This can lead to clear manifestations of the dangerousness of deep-buried structures constructed in complex rocky environments. For instance, owing to the evolution of many cracks in its lining after operating for only three years, the Xuecheng Tunnel of China were decommissioned and then restored after two years [7]. It should be pointed out that the high in-situ stress exerted particularly in weak rocks provoke huge durable deformations [8]. In addition to the fact that deep underground structures are qualified as high-risk structures [9], the coupling of the aforementioned situations further jeopardizes the lasting safety and stability of deep underground structures. On top of that, instability and rock rupture are often occurred in deep underground engineering due to the effects of rock creep and its major influencing factors. Creep is an unavoidable deterioration process of rocks in which nonlinear deformations are habitually occurred over time. It is strongly influenced by major factors that cannot be neglected. Its accurate prediction requires proper consideration of its main influencing factors. Since rock creep has a significant impact on the durability of deep underground structures, it is of great interest to consider it appropriately in the study of sustainable stability of deep rock engineering.

Numerous researchers have studied the long-term safety and stability of deep underground structures based on rock creep and found fruitful results. For instance, by studying the major risks associated with underground storage structures, Yang et al. [10] revealed that exorbitant creep was the predominant cause of failure of a deep cavern constructed in salt rocky media. They stress that it is necessary to carefully consider rock creep to avoid premature failure of deep rock engineering. To clarify the short and long-term stability of deep underground structures built in bedded marble, Chen et al. [11] analyzed creep test results to propose a time-dependent damage model for marble. Although their model is suitable for predicting the prolonged stability of deep underground structures located in marbled environments, it does not consider the effects of the main rock creep factors. On their side, Liu et al. [12] conceived a novel creep damage model for soft rocks using the classical Nishihara model, the superposition principle and the method of nonlinear least squares. Their novel model can be exploited to evaluate the stability of deeply buried structures situated in soft rocks and in particular in mica-quartz schist. Despite everything, their model could be applied more accurately if it took into acount the impacts of the main rock creep factors. Likewise, to forecast the long-term stability of deep energy storage structures, Wu et al. [13] considered relevant salt rock samples to establish an interesting constitutive model of rock creep, taking advantage of the theory related to fractional derivative. Afterwards, to assert the reliability of their model, they compare its parameters with those of a relevant hard rock and a relevant soft rock. However, in their model, among the major rock creep factors, only damage and stress level were considered. By taking advantages of Atangana-Baleanu fractional derivative theory, Deng et al. [14] proposed a complex creep constitutive model considering the factors such as hydraulic pressure, stress level and damage. To validate their model, they used typical triaxial experimental data of deep red sandstone. Despite its proven rationality, this complex model omitted the effects of temperature fluctuations which are generally notable at great depth. In order to guarantee proper safety of underground structures, Kamdem et et al. [15] established a workable creep constitutive model based on fractionel order derivative. Nonetheless, since such a model did not take into account the main rock creep influencing factors, its realistic application is difficult for a given underground structure. On their side, Yan et al. [16] proposed an integrated support system for a chinese deep roadway based on proper analysis of the creep and failure caracteristics of the concerned host rocks. To capture the specific creep of host rocks of ultra-deep storage structures in a saline rock environment, based on standard particle swarm optimization, Liang et al. [17] designed a very interesting constitutive creep model in which both temperature and damage are emphasized. However, since at very great depths the effects of water cannot be ignored, the precise application of such a model is difficult. Although there is a lot of research on rock creep, extensive research studies on the long-term stability of deep underground structures are still needed.

It should be emphasized that in deep underground emgineering, rock alteration is amplified by the major influencing factors of rock creep. Although fruitful progress has been attained by the research community, it remains an heavy task to take all these factors into consideration in most of the creep constitutive models. Thereby, it is still arduous to accurately ensure the prolonged stability of deep engineering structures particularly housed in complex rocky media. Studying rock creep with consideration of its major influencing factors can provide more precise outcomes in evaluating the long-term stability of deep rock engineering projects. Conviced of that, to predict the long-term stability of a deep tunnel located in complex soft rocky environments, Frenelus and Peng [18] conceived a two-variant creep constitutive model where rock damage and hydraulic pressure were taken into account. They demonstrated the importance of the effects of rock damage and hydraulic pressures on the overall stability of deep rock tunnels located in areas with complex geological and hydrological conditions. Additionally, they claim that another variant related to temperature variation can also be designed. In fact, it is recognized that one of the main causes of failure of deep underground structures is the degradation of the mechanical properties of the surrounding rocks. The deformation of the host rocks of these structures begins from the excavation period and evolves over time. The post-excavation stability should be durably ensured in order to guarantee the long-term safety and stability of deeply buried underground structures. To do so, particular consideration should be given to long-term creep and creep failure. Specifically, the effective characterization of rock creep taking into account its major influencing factors is of paramount importance. It should be noted that although many relevant research studies have already been successfully conducted, creep problems in deep rock engineering remain important and require continued in-depth investigations [19]. It is observed that in many research studies related to rock creep (e.g. existing creep constitutive models), the influences of the main factors affecting rock creep are not considered. Markedly, in some of them, not all the process of rock creep is accounted. For these reasons, it appears unrealistic to accurately use them for long-term stability studies of deep underground structures. The existence of variations in temperature, water, hydraulic pressure, stress level and damage factors is common in deep rock engineering. Hence, it of particular importance to thorougly study their effects on the creep behavior of deep rock engineering. The main purpose of this article is to elucidate the effects of major factors affecting rock creep process and the long-term safety and stability of deep underground structures such as tunnels. In fact, despite the great importance of these factors, there has not yet been a research study that profoundly emphasizes them. Effective consideration of these factors can help increase the degree of certainty in forecasting the time-dependent deformations in deep rock engineering. Consequently, the prolonged safety and stability of deeply buried underground structures can be more concise and accurate. In this way, creep-induced catastrophic failures can be effectively prevented in deep underground constructions. This paper can serve as a very good reference for any research aimed at predicting the sustainable safety and stability of deep rock engineering.

2. Effects of Major Rock Creep factors

Various major rock creep factors have been identified as having significant effects on the lasting safety and stability of deeply buried underground structures. Among them, temperature, water content, hydraulic pressure, stress level and damage are factors of immense consideration. To better understand them, it is necessary to decribe how they affect rock creep and the prolonged stability of the aforementioned structures. A typical creep curve of rocks is presented in Figure 1.

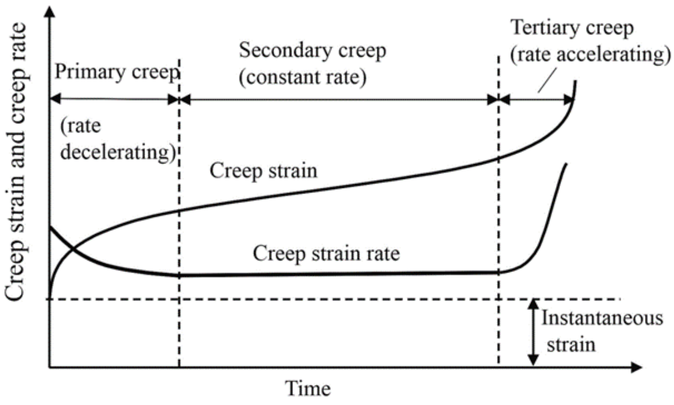


Fig. 1. A presentation of typical creep curve of rocks [19].

It is commonly known that the typical creep curves of rocks are characterized by four traditional phases [20, 21, 22], as shown in Figure 1. The first one is the instantaneous elastic phase which appears rapidly following the application of a constant load. The second phase, primary creep or attenuated creep, which is temporary, is characterized by a decelerated strain velocity. Steady creep, generally referred to as secondary creep, is the third creep phase in which the strain rate is consistent. The final creep phase is the tertiary creep where the creep rate is accelarated. It is important to point out that relevant experimental data are used in this article. They come mostly from triaxial compression creep tests carried out according to commonly established procedures. The rock samples utilized in the experiments were made under standard conditions and their dimensions are standard (diameter 50 mm and length 100 mm). In order to guarantee their relevenace, the rock samples were collected at great depth in typical deep underground openings.

2.1. Effect of Temperature

One of the main characteristics of deep underground engineering is elevated temperature. Often, the temperature fluctuates considerably at depth and the creep of rocks is greatly affected. In deep rocky environments, as explained by Li et al. [23], it can be quickly augmented and the rock mechanical properties can be impacted at large extents. Specifically, the spreading of cracks in rocks is facilitated by the increase in temperature [24]. Indeed, increase in temperature provokes the weakening of rock system, the reduction of effective stress and at the same time, there is increase of pore pressure [25], and there is generally degradation of rock properties [26]. High temperatures are not only caused change in the mechanical and physical properties of rocks [27], but also generate modification in rock microstructure [28]. In addition, the creep life is reduced at high temperature which accelerates tertiary creep and rock failure [29]. In some situations, even at low temperature, as studied by Martínez-Ibáñez et al. [27], it is observed reduction in relevant mechanical properties of rocks. Creep of all rock types is impacted by temperature. In the case of soft rocks such as salt rocks, temperature impacts on rock creep can even be greater [30]. Thereby, in the context of long-term safety and stability of deep underground engineering, the need to take into consideration the effects of temperature is increasingly urgent.

Based on a typical deeply buried tunnel situated in Guangxi province of China, the Weilai tunnel, a study thorougly investigated the effects of temperature on the creep behavior of the surrounding rocks subjected to cyclic load-unload. Relevant creep test data were adopted and obtained from Yang et al. [31], based on the criteria of similar rock type, similar typical in situ conditions, under load-unload cycles. A range of 90 h to 96 h was considered for the duration of each creep step, and the unloading process lasted between 20 h and 30 h. The surrounding rocks are predominantly argillaceous sandstone. Different deviatoric stresses are taken into account. This study also provides how the prolonged stability of such tunnel is affected by temperature variation. An illustration of the cyclic loading-unloading process is presented in Figure 2. It mainly presents the characteristic curve of loading-unloading cycles. To show the magnitude of the temperature effect, four types of temperatures ($10°C; 30°C; 40°C; 50°C$) are considered. The variation trend of mechanical properties of soft rocks subjected to temperature fluctuations is taken into account [32]. The results are displayed in figures 3 to 6.

It is worth mentioning that deep rocks exhibit their creep behavior during both loading and unloading conditions [33, 34, 35]. However, as the mechanical properties of rocks are damaged during loading conditions [36], the creep process of rocks under unloading conditions could be dramatic. Figure 2 illustrates the rock loading and unloading situations with appropriate explanations.

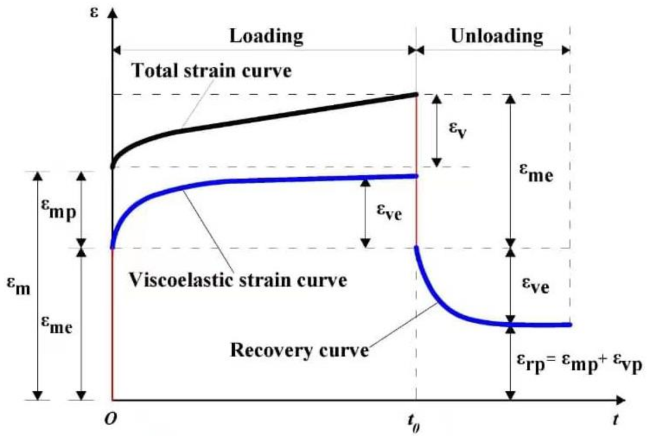


Fig. 2. Representation of typical creep curve in loading and unloading creep tests.

Figures 3 to 6 show that the impacts of temperature on the creep behavior of rocks are notable. This can be observed both during the loading phase and during the unloading phase. In the unloading stage, the situation can be more serious. Typically, rock mechanical properties are more affected by the unloading step than by the loading stage. In other terms, the unloading stage deteriorate the rock mechanical properties more quickly than the loading stage. Indeed, the mechanical properties of the rocks being weakened during the loading stage, they are easily and further altered during the unloading stage. Nevertheless, in both situations, creep strain increases, while creep life is reduced, with increasing temperature. At higher deviatoric stress, creep strain increases more rapidly and creep life is reduced more rapidly. The impacts of temperature change are even more pronounced at higher deviatoric stresses. In other words, high temperatures associated with high deviatoric stresses have more detrimental effects on the host rocks of deep underground engineering works. Under such conditions, the surrounding rocks become weaker and lose their ability to resist the applied loads and stresses.

It should be understood that, when it comes to the prolonged safety and stability of deep underground structures, the steady creep phase is the one that requires the greatest attention. In fact, in order to effectively ensure the long-term safety and stability of deep underground structures, the duration of the steady creep phase should be as long as possible. When the life of the steady-state creep phase is shortened by temperature variation, this seriously jeopardizes the prolonged safety and stability of the rocks surrounding any underground structure. When the tertiary creep phase is triggered, the long-term safety and stability are immediately affected and can no longer be guaranteed [18]. Due to the tertiary creep phase, the evolution is accelerated, causing instability until the rupture of the rocks hosting the concerned underground structures.

2.2. Effect of water content

Water has strong adverse effects on rock creep. Typically, it considerably diminishes the creep strength of rocks. As reported by Kinoshita and Inada [37], dry rocks generally have higher strength than wet rocks. Soluble rocks can be karstified when subjected to prolonged water action, which is common at great depth. Indeed, at great depth, groundwater flows are common and can attack the host rocks of a given deep underground structure. It is of primary importance to strongly take into account the presence of water when studying the creep behavior of deep rock engineering. In fact, the failure of deep underground structures under the effects of water is very frequent. In order to clarify the effect of water in rocks, the creep of a typical deep red sandstone has been investigated by Tang et al. [38]. The red sandstone samples were in dried condition and then immersed in water at 2, 4, 6 and 8 days, at same stress states. The results are displayed in Figure 7. It is shown that the longer the rock is immersed in water, the shorter its rock creep life. More widely, subfigures 7 (a) and 7 (b) illustrate the creep behavior of red sandstones in dried state and in water soaked state at 2, 4, 6 and 8 days, at same stress conditions. Samples in the dry state, where the creep strain rate progresses slowly with time, exhibit a longer time-to-failure. Subfigures 7 (a-1) and 7 (b-1) show enlarged views of the creep strain and creep strain rate curves of the rock samples. The samples are also immersed in water at 4 days, 6 days and 8 days. To provide more details on how water content affects the creep behavior of rocks, relevant results are presented in Table 1 for various rock types.

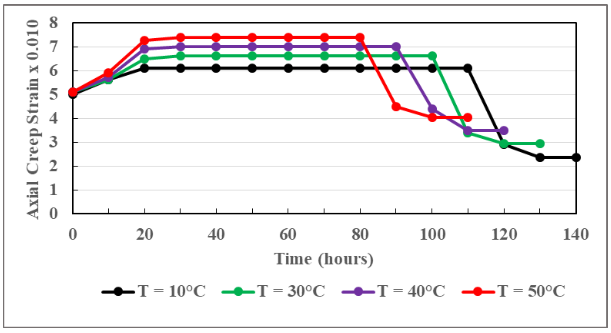


Fig. 3. Effects of temperature on the creep strain of sandstone under a deviatoric stress of 11.99 MPa.

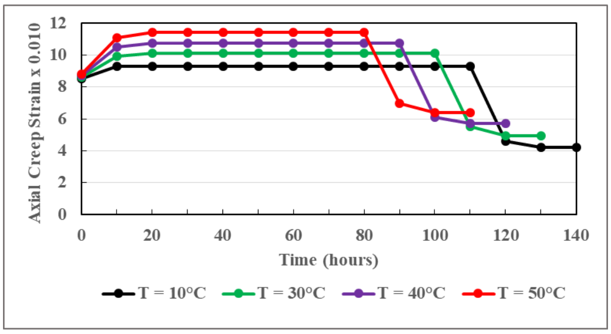


Fig. 4. Temperature impacts on the creep strain of sandstone under a deviatoric stress of 17.99 MPa.

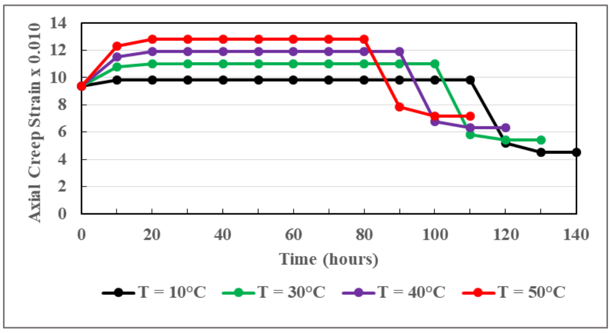


Fig. 5. Temperature impacts on the creep strain of sandstone under a deviatoric stress of 20.97 MPa.

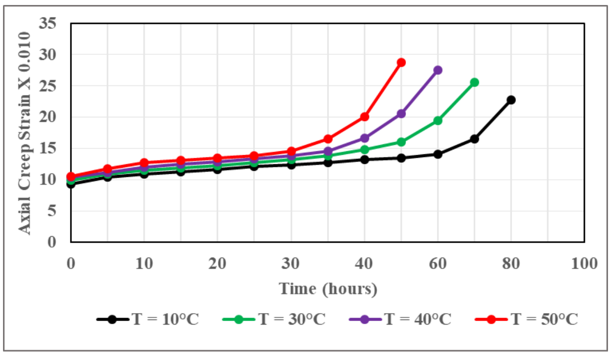


Fig. 6. Temperature impacts on the creep strain of sandstone under a deviatoric stress of 23.98 MPa.

Table 1. Relevant results of the effects of water content on the creep behavior of rocks

Rock type	Specimen conditions	Testing type	Effect of water content on rock creep	Study
Green Mudstone	Immersed in water	Uniaxial compressive strength test; Creep tests	Creep failure occurs at lowest stress level and the shortest time-to-failure.	Li et al. [39]
Argillaceous siltstone	Immersed in water	Triaxial compression rheological tests	Instantaneous strain, creep strain, and steady creep strain rate are increased; Time-to-failure is shortened.	Lin et al. [40]
Granite, Marble, and Sandstone	Saturated in water	Uniaxial compression tests and acoustic emission	The elastic modulus, critical strain, and uniaxial compressive strength are greatly reduced.	Cai et al. [41]
Red Sandstone	Immersed in water	Multistage creep tests	Increased creep strain and creep strain rate; Reduced time-to-failure and stress threshold.	Yu et al. [42]
Andesite	Saturated in deionized water	Uniaxial compression tests	Notable reduction of creep lifespan which can be up to 180 times shorter.	Hashiba et al. [43]
Limestone	Saturated and immersed in water	Triaxial compression creep tests	Both strain and creep strain rate increase due to increasing water content.	Liu et al. [44]

2.3. Effect of hydraulic pressure

Hydraulic pressure is another major factor that significantly affects the creep behavior of rocks. Water, as previously explained, considerably diminishes the creep life of rocks. Rock creep is further impacted by pressurized water. As such, hydraulic pressure is a huge concern on the host rocks of deep underground constructions. Its effects are usually considerable, regardless of the rock types. Long-term actions of hydraulic pressures cause inevitable deteriorations of the mechanical properties of rock materials [45, 46]. It should be reminded that rocks are non-homogeneous materials filled with pre-existing cracks and fractures [18]. Under the action of hydraulic pressures, these cracks and fractures propagate and develop widely and generalize the damage to the rocks [44, 47, 48]. By weakening the strength of rocks, hydraulic pressure plays a major role in the rock fracture process. As a relevant mechanical characteristic of rocks, creep is profoundly influenced by hydraulic pressures. In fact, as experimented by Liu et al. [44] and Liu et al. [49], rocks exhibit reduced creep strain and increased peak acceleration creep velocity under increased hydraulic pressures. Furthermore, increasing hydraulic pressure results in decreased creep failure time. In fact, creep strain rate can be augmented following the increase of hydraulic confining pressure [44]. It can be understood that hydraulic pressures can shorten the rock creep life. In order to further reveal how hydraulic pressure affects the creep behavior of rocks, a typical rock has been studied by Lv [50]. To do this, four levels (0 MPa, 0.5 MPa, 1.0 MPa, and 1.5 MPa) of hydraulic pressure were considered, as presented in Figure 8.

Figure 8 confirms that creep stress increases as hydraulic pressures increase. That is, higher hydraulic pressures provoke higher creep strains. In other terms, the creep process progresses more rapidly under higher hydraulic pressures. The higher the hydraulic pressures, the more the rocks are weakened and the more rapidly tertiary creep and failure occur.

The effects of hydraulic pressures on rock creep are extensively studied in Frenelus and Peng [18]. Indeed, based on loading-unloading cycles and considering the host rocks of a deep tunnel in Guangxi province of China, Frenelus and Peng [18] conceived a creep constitutive model in which the second variant takes into consideration the effects of hydraulic pressures as below:

$$\varepsilon_{ij}(t,\sigma,p)=\begin{cases}\dfrac{1}{2G_1(\sigma,\ p)}S_{ij}+\dfrac{1}{2G_2(\sigma,p)}\left[1-exp\left(-\dfrac{G_2(\sigma,\ p)}{\eta_2(\sigma,p)\alpha}t^{\alpha}\right)\right]S_{ij} & (S_{ij}<S_s)\\ \dfrac{1}{2G_1(\sigma,\ p)}S_{ij}+\dfrac{S_{ij}-S_s}{G_p(\sigma,\ p)}+\dfrac{1}{2G_2(\sigma,\ p)}\left[1-exp\left(-\dfrac{G_2(\sigma,p)}{\eta_2(\sigma,\ p)\alpha}t^{\alpha}\right)\right]S_{ij}+kS_{ij}\left(\dfrac{t}{\eta_3(\sigma,p)}\right)^{n}\left(e^{-\beta(\sigma,\ p)t}\right)^{(1-n)} & (S_{ij}\geq S_s)\end{cases} \quad (1)$$

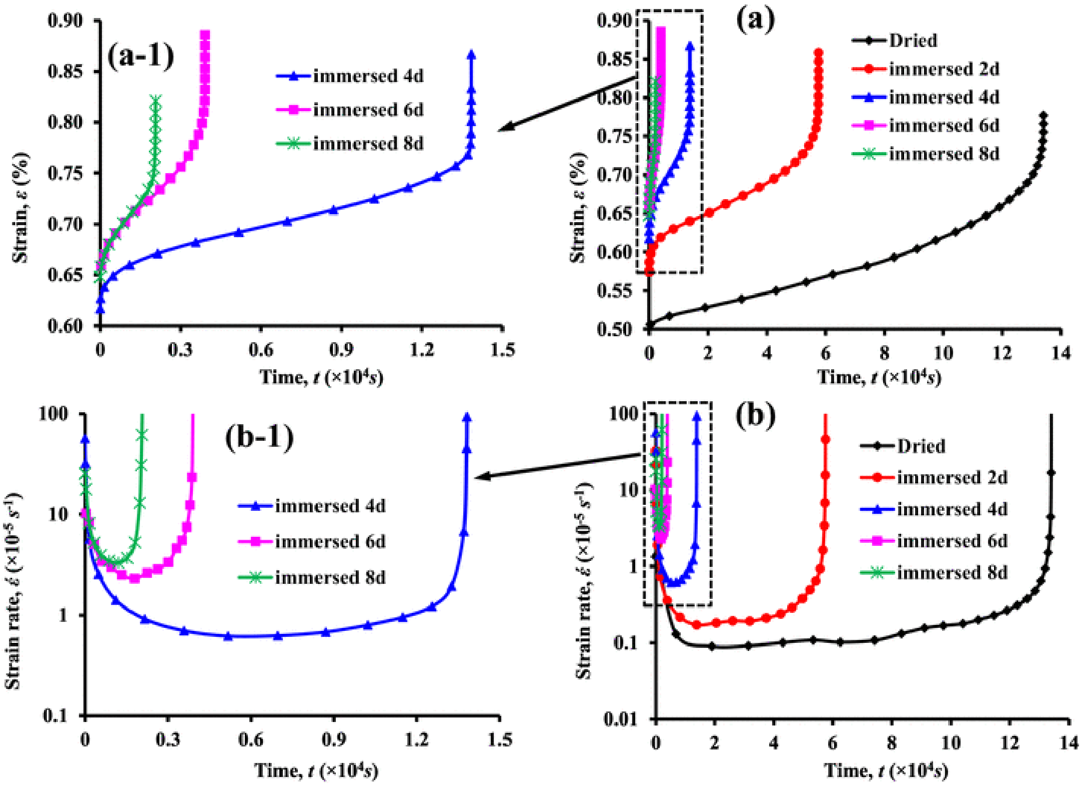


Fig. 7. Effect of water on creep features of red Sandstone [38].

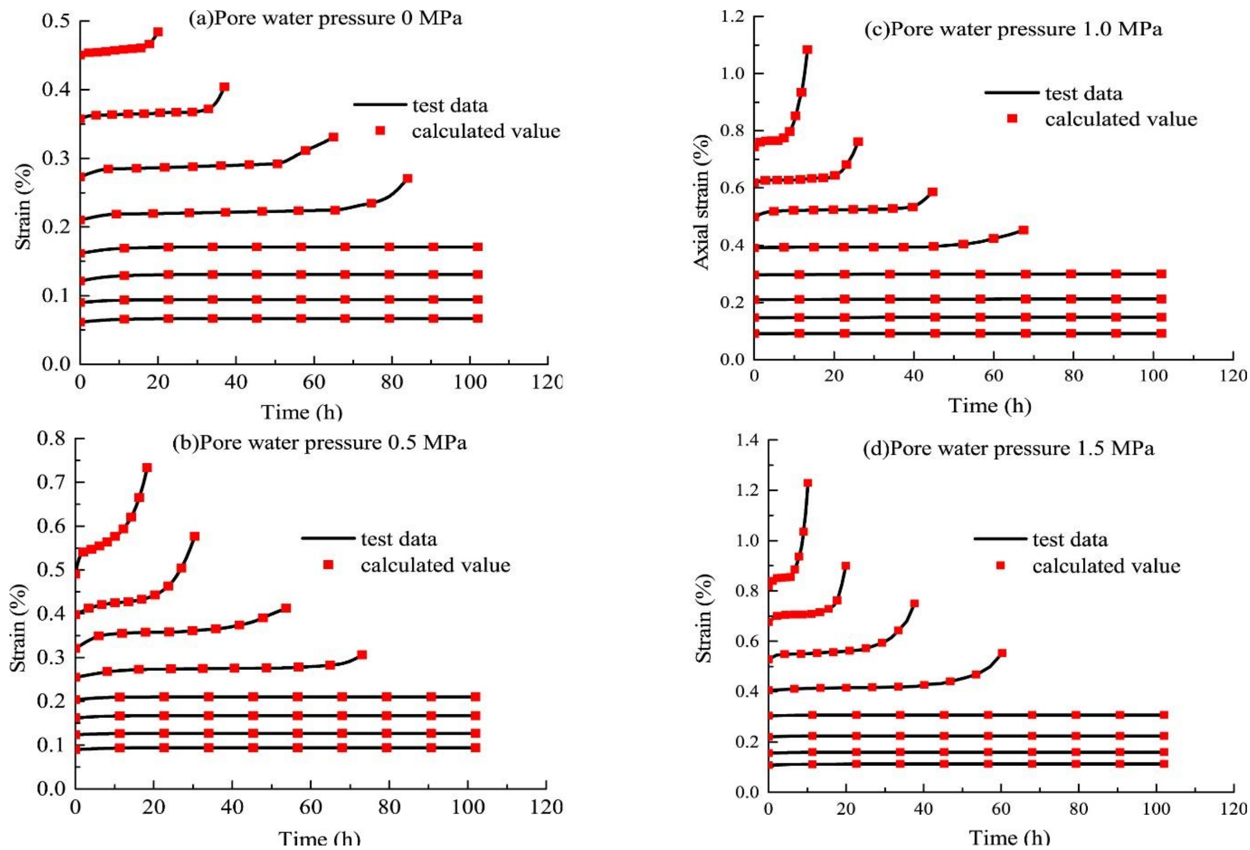


Fig. 8. Illustration of hydraulic pressure effect on the creep behavior of a typical rock [50].

Here $\varepsilon_{ij}(t,\sigma,p)$ is the creep strain of the host rocks mainly affected by stress, hydraulic pressure; S_{ij} stands for deviatoric stress tensor; S_s represents the long-term strength of rocks in three-dimensional form; G_1 stands for shear modulus of rocks; G_p denotes the instant rock shear modulus; G_2 is the visco-elastic shear modulus; η_2 is the coefficient of shear viscosity; η_3 represents the coefficient for the initial viscosity of the viscoplastic body; t is creep time; k and n are constant related to rock materials; $\beta(\sigma,p)$ represents a material constant which is simultaneously affected by hydraulic pressure (p) and stress (σ). Considering the cyclic loading-unloading, Figures 9 and 10 show the effects of hydraulic pressures on the creep behavior of rocks based on Equation (1), under deviatoric stress of 11.99 MPa and 17.99 MPa.

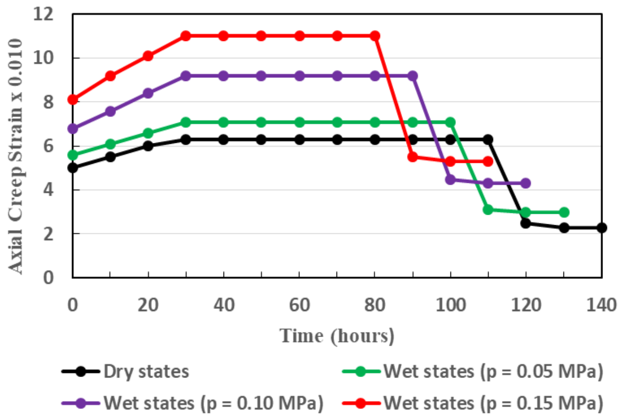


Fig. 9. Effects of hydraulic pressure on the creep strain of sandstone in loading-unloading states under a deviatoric stress of 11.99 MPa [18].

Figures 9 and 10 illustrate the influence of hydraulic pressures on the evolution of rock creep, both at loading and unloading conditions. It can be seen that hydraulic pressures have great influence in the evolution of rock creep. As hydraulic pressures increase, creep stress increases and rock life decreases. Specifically, the higher the hydraulic pressures, the faster the creep process evolves. The rapid evolution of the creep process is very detrimental to the safety and stability of deep underground structures, because it decreases the duration of steady creep and accelerates the onset of tertiary creep. Consequently, hydraulic pressure destabilizes the resistance of the rocks. It diminishes the duration of the loading stage and that of the unloading stage. Thereby, the higher the hydraulic pressure, the shorter the duration of the loading and unloading processes. Table 2 provides a summary of the pertinent effects of hydraulic pressures on the creep behavior of different rock types.

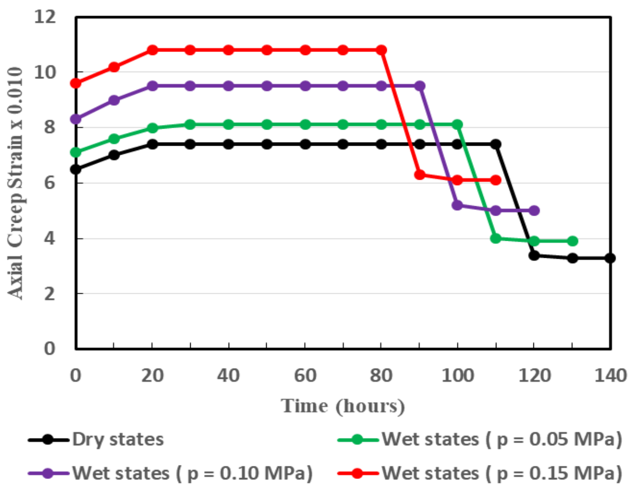


Fig. 10. Effects of hydraulic pressure on the creep strain of sandstone in loading-unloading conditions under a deviatoric stress of 17.99 MPa [18].

2.4. Effect of stress level

Concerning the stress level, it can be regarded as the engine governing the magnitude of the creep stages. This is explained by the fact that creep behavior is ordinarily displayed when a specific stress is applied to rock materials. For example, by increasing the shear stress for the same elapsed time, there is also an increase in creep strain and steady-state creep strain rate [55]. By increasing the deviatoric stress, it also leads to the increase in creep strain rate [25]. It is recognized that rock creep parameters are changed when the stress level is modified. Figure 11 illustrates the influence of stress level on the creep behavior of rocks.

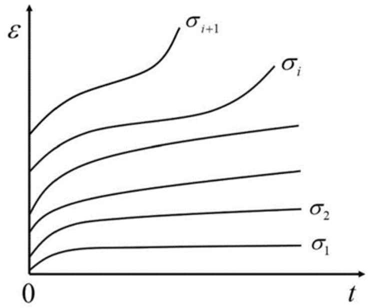


Fig. 11. Illustration of creep curves of rocks under different stress levels.

Generally, as already shown in Figure 11, four phases of creep (instant elastic creep, primary creep, secondary creep and tertiary creep) are observed in rock materials when subjected to sustained loads. Figure 11 shows that the stress level gouverns the overall creep process. Indeed, the appearance of major creep phases is dependent of the stress level. Under a certain stress level, the secondary creep and tertiary creep could not be triggered. Creep lifetime is reduced as the stress level increases, because the total creep stage increases rapidly. There is a stress threshold from which some creep stages can be occurred. This threshold corresponds to the magnitude of the stresses which cause the first cracks in the rocks [18, 56]. However, It should be noted that the axial and laterial directions of rocks can have their stress thresholds different. In general, when the stress level overtakes the stress threshold, there is appearance of the secondary creep, then the tertiary creep [57, 58]. When the applied stress is below the stress threshold, the rocks exhibit only primary creep [59]. Specifically, as pointed out by Gao and Yin [60], the stress level below the long-term strength of the rocks can be considered as the one that triggers the secondary creep stage.

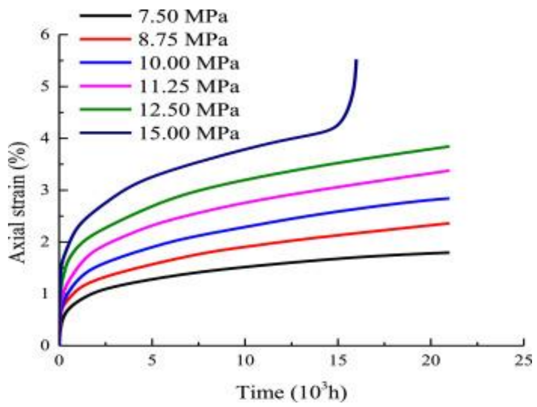


Fig. 12. Display of creep curves of a typical rock salt at different stress levels [61]

To sum up, stress level remains a major rock creep factor that cannot be neglected. Through it, the overall creep phases may or may not appear. The stress level can potentially facilitate a longer or shorter duration of the secondary creep stage. Proper control of stress level is of tremendous importance for the long-term safety and stability of deep underground structures. As illustrated in Figure 12, six stress levels are taken into account to study the creep process of a typical rock salt. It is clearly demonstrated that the creep process evolves as the stress level evolves. At a stress level of 15 MPa, all stages of creep are represented. At such a stress level, the steady-state creep phase is shortened and rapidly promotes the onset of the tertiary creep phase where deformations develop in an accelerated manner. On the contrary, at a low stress level such as 7.50 MPa, the tertiary creep phase does not occur. As already explained, the longer the duration of secondary creep or steady creep, the more safety and stability of rock engineering is guaranteed, since tertiary creep will not emerge quickly. Thus, in deep rock engineering, it is of primary importance to pay attention to the stress level that will not promote the rapid onset of the tertiary creep phase, but will keep the steady creep phase as long as possible.

2.5. Effect of damage

Due to the pre-existing microcraks and microvoids in rock materials [62], rock damage is inevitable. In fact, rock damage gradually evolves by subcritical growth and sinergy of cracks [63]. During and after excavation of the rocks surrounding deep underground structures, owing to the redistribution of stresses around the openings, there is formation of the two main impacted zones that called excavation damaged zones (EDZ) and excavation disturbed zones (EdZ) (Figure 13). It is understandable that the more natural rocks are initially damaged, the more their damage extends into the aforementioned areas. Moreover, since the excavation methods impose additional damage to rocks hosting the openings, the extent of damage to the mentioned zones is more important with time. It should also be noted that dynamics events also cause increased damage to rocks.

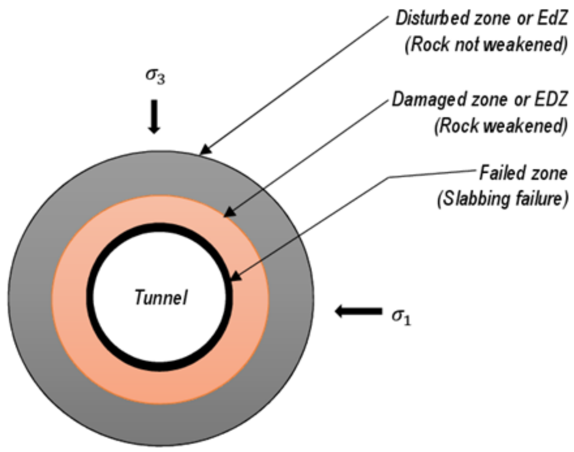


Fig. 13. Typical position of the EDZ and EdZ in a deep circular tunnel subjected to common principal stresses σ_1 and σ_3 [64].

In the EDZ which is the immediate zone formed throughout the excavation limit [64, 65], the relevant rock properties are deeply affected since there are permanently damaged [64, 66-68]. Markedly, the evolution of damage is nonlinear [69], due to fact that microcracks are typically distributed randomly in rooks. Ordinarily, after accumulation of damage in the secondary creep [70], tertiary creep stage are prone to be started. Specifically, tertiary creep is mainly occurred by serious damage [71], and failure will inevitably happen by the fact that extreme damage has severely weakened the mechanical properties of rocks [72]. Importantly, the damage factor (D) fluctuates from 0 to 1. For intact rocks, D = 0; and for rocks fully damaged, D = 1 [73, 74]. One pertinent expression of the damage factor (D) is as follows:

$$D = 1 - \left(1 - \frac{t}{t_c}\right)^{\frac{1}{1+\delta}} \tag{2}$$

Here t represents the initial time; t_c denotes time of the total damage of rocks; δ is a constant related to the rock material.

The damage of rocks can also be written by considering the energy dissipation concept, where U_0 is the critical strain energy associated to initial damage; and U which is the strain and is given [74]:

$$U = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij} \tag{3}$$

Here $(ij = 1,2,3)$, σ_{ij} stands for stress tensor, ε_{ij} denotes strain tensor; σ_1, σ_2, σ_3 traduce the principal stresses. In positive compression, $\sigma_1 \geq \sigma_3 = \sigma_2$. Thereby, rock damage can be globally modelled as follows [74]:

$$\begin{cases} D = 0 & (U < U_0) \\ D = \dfrac{U - U_0}{\alpha U_0} & (U_0 \leq U < (1+\alpha)U_0) \\ D = 1 & (U \geq (1+\alpha)U_0) \end{cases} \tag{4}$$

Here α is a parameter associated with the materials properties.The damage factor controls the overall creep behavior of rocks. In particular, tertiary creep duration is generally shortened and rock failure is triggered faster when damage factor is critical. The evolution of damage has severe effects on the overall process of rock creep. Even the effects of initial damage on rock creep are not negligible, they are quite considerable [75]. To clearly show how damage affect rock creep, Frenelus and Peng [18] established a creep constitutive model based on load-unload cycles considering the surrounding rocks of a deep-buried tunnel in Guangxi province of China. The main equations are as follows:

$$\varepsilon_{ij} = \begin{cases} \frac{1}{2G_1}S_{ij} + \frac{1}{2G_2}\left[1 - exp\left(-\frac{G_2}{\eta_2\alpha}t^\alpha\right)\right]S_{ij} & (S_{ij} < S_s) \\ \frac{1}{2G_1}S_{ij} + \frac{S_{ij} - S_s}{G_p} + \frac{1}{2G_2}\left[1 - exp\left(-\frac{G_2}{\eta_2\alpha}t^\alpha\right)\right]S_{ij} + kS_{ij}\left(\frac{t}{\eta_3}\right)^n (1-D)^{(1-n)} & (S_{ij} \geq S_s) \end{cases} \quad (5)$$

Table 2. Pertinent results of the effects of hydraulic pressures on the creep behavior of rocks

Rock type	Specimen conditions	Testing type	Effect of hydraulic pressures on rock creep	Study
Red Sandstone	Saturated water	Triaxial creep tests	Increasing hydraulic pressure results in a decrease in peak strength and modulus of elasticity. Creep strain rate augmets as hydraulic pressure augments.	Yang et al. [51]
Mudstone	Saturated water	Creep tests	The creep characteristics of mudstone deteriorate as hydraulic pressure increases.	Gao et al. [52]
Granite	Soaked in water	Hydro-mechanical tests	Hydraulic pressure reduces the strength of granite and causes shear fracture.	Cheng et al. [53]
Limestone	Saturated and immersed in water	Compression creep tests	Increasing hydraulic pressure results in increasing creep strain and creep strain rate.	Liu et al. [44]
Sandstone	Vacuumed and immersed in water	Creep tests	Both creep strain and steady creep strain rate are increased by increasing hydraulic pressure.	Luo et al. [54]
Shale	Soaked in water	Shear-creep–seepage test	The smaller shear stresses at each creep stage are the result of the larger hydraulic pressures.	Li et al. [46]

The meaning of the parameters is the same as in Equation (1). In order to clearly illustrate how the variable damage affects rock creep, 4 damage indexes (δ) are taken into consideration (0.2; 0.4; 0.6; 0.8). By the damage index δ, the effects of damage are shown in Figures 14 and 15.

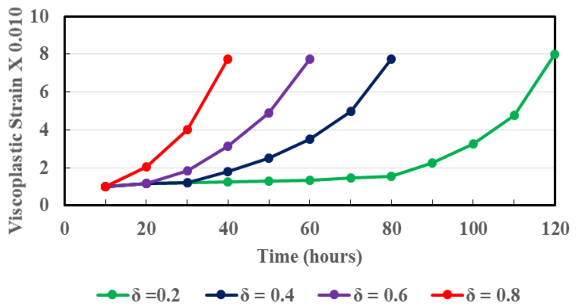


Fig. 14. Representation of the viscoelastic strain of the model based on different damage index [18].

As shown in Figures 14 and 15, the highest damage index values correspond to the highest damage scope in the rocks. Via Figure 14, it is shown that, the more the rock is damaged, the shorter the viscoelastic strain. Figure 15 reveals that the highest damage index is associated with the damage extent in the rocks. Hence, rock creep greatly affected by rock damage which is unavoidable during and after tunneling. The more the rocks hosting the underground structures are damaged, the shorter their time-to-failure. In this sense, failure can occur at any time, when all the rock's resistance reserves are exhausted or when the damage reaches its critical stage. Consequently, adequate measures are imposed in deep rock engineering to appropriately mitigate the effect of damage on rock creep in order to ensure the long-term safety and stability of deep underground structures. Indeed, diverse means can be used to predict rock failure. Among them, the scope of damage in rocks should be reliably monitored [76]. Normally, to better guarantee the prolonged stability of deep underground structures, the evolution of all the major rock creep factors should be appropriately monitored.

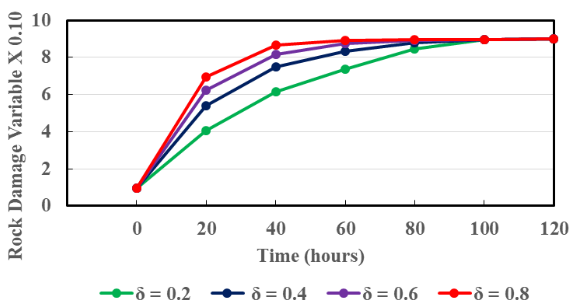


Fig. 15. Effect of damage on the surrounding rocks of a deep-buried tunnel [18].

3. Creep and Convergence deformation in deep underground structures

Influenced by the evolution of time, the convergence deformation is the progressive closure of the surrounding rocks of a given underground structure after excavation (Figure 16). The convergence deformation is constituted by the tunnel front advance deformation and the creep deformation [21,77,78]. However, its evolution is predominantly governed by rock creep. The total convergence of a given underground structure can be estimated as follows [78; 79]:

$$C(x,t) = C_{\infty x}\left[1 - \left(\frac{X}{x+X}\right)^2\right]\left\{1 + m\left[1 - \left(\frac{T}{t+T}\right)^n\right]\right\} \quad (6)$$

Here $C(x,t)$ traduces the total convergence in a section of an underground structure at a distance x from the face, and after a time t; $C_{\infty x}$ stands for instant closure and can be estimated at remote distance from the face; X denotes a reference distance controlling the effect of the tunnel face; T is the time characteristic related to the time-dependent response of the system; n is an exponent taking into account the time-dependent contribution of the convergence; m represents a parameter accounting the ratio between the instant convergence and ultimate total convergence.

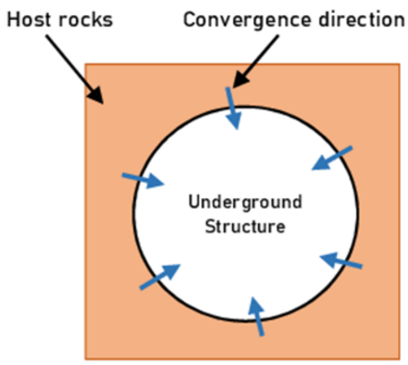


Fig. 16. Illustration of the convergence tendency in a typical circular underground structure.

Rock creep being a form of rock engineering deterioration, convergence deformation is a type of structural disease occurring in deep underground openings. The best way to control the convergence rate of deep underground structures is to properly control the evolution of rock creep. That is, the creep strain rate should be slow enough to allow a long-lasting steady creep phase. In fact, a longer steady creep phase will tend to further stabilize the convergence rate of deep rock engineering. In this sense, it is essential to take into account any factor that may increase creep expansion and convergence rate in the surrounding rocks of deeply buried underground structures. It should be noted that, as underground structures remain large-scale structures, their proper durability is required [80]. To achieve the durability goal of deep underground structures, mastering the major influencing factors of rock creep is of particular consideration. Above all, since geological unknowns exist in the underground spaces and must not be overlooked [81], it is very necessary to pay any attention aiming at guaranteeing the prolonged stability of rock engineering civil works. In fact, it is worth emphasizing that not only extreme convergence deformations in terms of extreme rock creep will lead to the final closure of underground openings, but it will also end their service life, and this could happen prematurely if appropriate countermeasures are not taken in right time. It should be noted that over time, other structural diseases will inevitably emerge in deep underground structures whose long-term stability will be seriously threatened [82, 83]. In view of this situation, the creep of the host rocks of deep underground constructions must be appropriately supported and monitored. At least, given its utmost importance in maintaining the prolonged safety and stability of rock engineering, the steady creep phase requires adequate monitoring. the entire creep process should be monitored and this should be done continuously [84]. In fact, referring to Imani et al. [85], monitoring creep phases can help to further characterize rock creep. To effectively do so, the major factors influencing rock creep must be carefully monitored. Suitable remote sensing systems can be promising for adequate long-term monitoring in deep underground structures [86-88]. Remote sensors such as 3D laser and Fiber Bragg Grating (FBG) sensors can monitor the convergence deformation of underground constructions [89, 90]. Likewise, in deep underground structures, tempretaure fluctuation can also be monitored by adaquate remote sensors such as raman sensors [91, 92]. Variation in water content, stress level and damage can be monitored by FBG sensors [93, 94]. Hydraulic pressure can be monitored by seepage pressure gauges [95, 96]. For more fruitful monitoring results, remote sensors can also be combined with other suitable monitoring techniques.

4. Discussions

Deep rocky environments are of particular focus since their conditions become more and more complex as the burial depth of underground structures increases. In fact, rock creep usually receives a lot of attention because it is widely applied to the study of the long-term safety and stability of deep rock engineering. The creep features of rocks are utilized as suitable means for making proper decisions regarding the technical feasibility of deep underground projects such as tunnel construction, mining, and so on. Adequate support systems of deep rock engineering are generally designed by employing adequate constitutive models of rock creep. It is in this perpective that Yang et al. [97] proposed a robust support system to deal with strong instability caused by creep problems in a deep siltstone roadway. The extraordinary deformation of a deep soft rock roadway which is housed in the Pingdingshan mining area of Henan Province, China, has been restrained by a robust mixed support system based on the creep constitutive model of a deep sandy mudstone [98]. It should be noted that the operational lifespan of underground structures is most often expected to last many years (a hundred years or more). It is therefore more than necessary that their long-term safety and stability are properly ensured. Knowing that such kind of stability is strongly linked to rock creep [21, 99], it is of great interest to take into consideration the major factors that affect it. Indeed, creep problems in deep rock engineering are significant and required to be addressed thoroughly. In many existing creep constitutive models, the strong influencing factors of rock creep are always not taken into account. Markedly, in some of them, not all the process of creep is accounted. For these reasons, it seems unrealistic to accurately use them for long-term stability study of deep underground structures.

Modelling adequate creep constitutive models to analyze the long-term stability of deep rock underground structures is a required task. However, trends aimed at optimizing constitutive models of rock mechanics should be prioritized [100]. Specifically, pertinent constitutive models may be accompanied by relevant variants that could take into account the effects of the main factors of rock creep. In fact, it is very important to point out that, in spite of many relevant recent advancements, as related by Sainoki et al. [101], it is still difficult to ensure long-term safety and stability of deep rock engineering. This is due by the fact that, deep rock engineering is increasingly complex, as the burial depth of underground structures increases. It should be reminded, as previously detailled, the major rock creep factors greatly vary with increasing burial depth of deep rock engineering projects. This undoubtedly poses a serious threat to the expected service life of deep underground structures. Furthermore, the tunnelling conditions generally vary with the regional geological, hydrological, and other relevant conditions of the deep rock engineering. Thereby, it is significant to conduct special research studies for a given underground structure in order to better ensure safety and stability.

All the major factors (temperature, water content, stress level, hydraulic pressure, damage) described above significantly affect rock creep. Specifically, they all diminish the duration of the steady creep phase and hasten the triggering of the tertiary creep phase, and consequently reduce the rock time-to-failure and rock creep lifespan. In other words, they govern the rock creep life and limit the prolonged safety and stability of deep underground structures as illustrated in Figure 17.

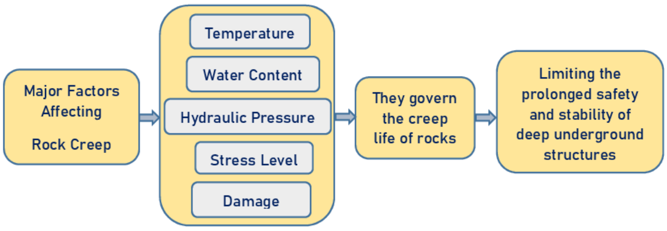


Fig. 17. Main rock creep factors and their effects on rock creep.

The combination of these factors could be more harmful to rock creep life. In fact, their coupled effects can be encountered in deep rock engineering. This can be occurred since deep rock engineering is simultaneously characterized by elevated stress, elevated temperatures and high hydraulic pressures. In addition, in many situations, the main factors of rock creep can be fluctuated during the exploitation life of deep underground structures. Inevitably, over time, deep rock engineering structures are susceptible to be damaged at varying scales. Construction breaches are among the typical causes of damage in deep underground structures [102]. It is important to note that variation in some rock creep factors promotes variation in other rock creep factors. Proper assurance of structural integrity relies on effective capture of the time-dependent behavior of deep rock engineering [103]. Adequate countermeasures are therefore imposed to minimize the effects of rock creep major influencing factors in deep underground structures. It is important to note that, in deep underground engineering, some uncertainties should not be ignored [104-107]. In this sense, a tremendous precaution is that rock creep must be adequately monitored during the operational life of deep underground structures. The selection of the best method for monitoring creep in the rocks surrounding such structures is of particular interest and should be given priority [108]. Indeed, it should be noted that adequate monitoring of rock creep will also result in monitoring the evolution of its major influencing factors in deep underground engineering. In other words, the following rock creep factors should be carefully monitored in the host rocks of deep underground structures: temperature variations, water content variation, hydraulic pressure rise, stress level fluctuation and damage evolution. Besides, all the structural components of such structures need proper monitoring system to effectively guarantee their prolonged safey and stability and thus prevent their premature failure. Hence, suitable measures can be taken into consideration as early as possible to effectively ensure the lasting safety and stability of deep rock engineering.

5. Conclusions and future research directions

5.1. Conlusions

In this article, the main contribution is to highlight the major factors affecting rock creep and show how they control the prolonged safety and stability of rock engineering. The pertinent conclusions drawn are as below:

1) Rock creep is affected by diverse major factors such as temperature, stress level, water content, hydraulic pressure, and damage. Overall, their impacts on rock creep process in deep rock engineering are significant. Under the increase of these factors, the steady creep phase lifetime and the time-to-failure of rocks are decreased, and the tertiary creep phase is triggered very quickly. These major rock creep factors pose severe risks to the prolonged safety and stability of deep underground structures.
2) Under the action of these major factors, creep strain rate evolves rapidly to the point of reducing the overall creep life of the rocks surrounding the underground structures. As a result, this accelerates the onset of the tertiary creep, and creates immediate instability of the host rocks. Whatever the factor that triggered it, the tertiary creep phase is considered a major warning signifying the emergence of instability of deep underground structures. Whether during loading or

unloading phase, the higher the temperature, the shorter the duration of the steady creep phase and the faster the onset of the tertiary creep phase. Likewise, the higher the stress level, the shorter the creep process, and the faster the time-to-failure of rocks. The greater the extent of the damage, the weaker the host rocks, and the shorter their time-to-failure. Similarly, the higher the water content, the faster the appareance of the tertiary creep stage. The highest hydraulic pressures cause the shortest creep process and the fastest onset of tertiary creep.

3) The effect of one factor may facilitate the occurrence of another factor and the coupled effects are more serious for the safety and stability of structures. Temperature fluctuations, for example, can generate additional damage to rocks and thus facilitate the circulation or accumulation of water and hydraulic pressures in the surrounding rocks of deep underground structures. There is an urgent need to address the effects of major rock creep factors in order to effectively ensure adequate structural integrity and prolonged safety and stability of deep underground constructions.
4) A serious form of structural disease in rock engineering is convergence deformation of deep underground structures. Its extent is majoritarily composed of creep deformations. One of the best ways to control the convergence deformation of deep underground structures is to precisely control the creep deformation of the surrounding rocks. Therefore, when predicting or evaluating rock creep in underground engineering, the necessity to consider the major factors mentioned above is of great interest. Appropriate predictions of creep in host rocks will enable accurate estimation of the convergence tendency of underground constructions. Subsequently, adequate supports systems are required to control the convergence deformations in terms of creep deformations in deep rock engineering.
5) The major rock creep factors significantly affects the prolonged safety and stability of deep underground structures. Weathering of rocks and structural failure are caused by prolonged creep deformation. To preserve the integrity of deep underground structures by limiting their creep deformation, it is required that the steady creep stage be maintained for as long as possible. Hence, suitable measures are imposed for these structures. Such measures may include designing adaptive and accurate creep constitutive models, and conceiving the most appropriate support systems for deep underground structures. Besides, rock creep evolution should be controlled and adequately monitored during the lifetime of the concerned underground structures.

5.2. Future research directions

Regarding the prolonged safety and stability of deep underground structures, rock creep remains an open and hot research topic and becomes a substantial focus of interest in rock mechanics and engineering. Future research directions should attempt to address the following main points.

1) For a given deep underground structure located in complex or relatively complex rocky environments, it is of great consideration to effectively study its prolonged stability by modelling novel suitable creep constitutive models considering the coupled effects of temperature, water content, hydraulic pressure, stress level and damage. Different relevant variants of creep constitutive models can be appropriately established.
2) It is of utmost importance to determine the duration of the steady creep phase for the surrounding rocks of deep underground structures which are simultaneously affected by temperature fluctuations, varying stress levels, varying water contents and hydraulic pressures and varying degrees of damage.
3) Since the safety and stability of deep underground structures depends primarily on the stability of their regional rocky environments, it is essential to estimate the actual time-to-failure of the surrounding rocks affected simultaneously by temperature fluctuations, varied stress levels, varied water contents, damage extents and hydraulic pressures.
4) All the major rock creep factors cause alteration of rock mechanical properties. It is extremely important to estimate the resistance reserve of rocks surrounding deeply buried structures after being affected by the aforesaid factors.
5) Effectively monitoring the evolution of rock creep should become a priority in deep rock engineering. Different reliable monitoring methods can be considered in order to achieve successful monitoring results. Nowadays, remote sensing tools are promising in underground engineering. They can be associated with other techniques to provide robust and reliable monitoring outcomes. Appropriate decisions can be made in the shortest possible time, and excessive expenditure on possible repair work can be avoided. Thereby, the safety and stability of deep underground structures can be ensured at all times.

Author contributions

Conceptualization, W.F.; methodology, W.F.; software, W.F; validation, H.P.; formal analysis, W.F.; investigation, W.F.; resources, W.F.; data curation, W.F.; writing—original draft preparation, W.F.; writing—review and editing, H.P.; visualization, H.P.; supervision, H.P.; project administration, H.P.; funding acquisition, H.P. All authors have read and agreed to the published version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

No funding was received to assist with the preparation of this manuscript.

Conflicts of Interest

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Data availability

All relevant data related to this manuscript are available and can be provided upon reasonable request.

References

1. Zhang GH, Jiao YY, Wang H. Outstanding issues in excavation of deep and long rock tunnels: a case study. Canadian Geotechnical Journal. 2014; 51(9): 984-994. https://doi.org/10.1139/cgj-2013-0087
2. Wagner H. Deep Mining: A Rock Engineering Challenge. Rock Mechanics and Rock Engineering. 2019; 52:1417–1446. https://doi.org/10.1007/s00603-019-01799-4
3. Chen J, Zhao J, Zhang S, Zhang Y, Yang F, Li M. An Experimental and Analytical Research on the Evolution of Mining Cracks in Deep Floor Rock Mass. Pure and Applied Geophysics. 2020; 177: 5325–5348. https://doi.org/10.1007/s00024-020-02550-9
4. Fan L, Wang W, Yuan C, Peng W. Research on large deformation mechanism of deep roadway with dynamic pressure. Energy Science and Engineering. 2020; 8: 3348–3364. https://doi.org/10.1002/ese3.672
5. Feng X. Experiment and Numerical Simulation on Creep Mechanical Behaviors of Mudstone under Unloading Condition. Geofluids. 2022; 2022: 7175774. https://doi.org/10.1155/2022/7175774
6. Tran-Manh H, Sulem J, Subrin D. Progressive degradation of rock properties and time-dependent behavior of deep tunnels. Acta Geotechnica. 2016; 11: 693–711. https://doi.org/10.1007/s11440-016-0444-x
7. Xu G, Gutierrez M. Study on the damage evolution in secondary tunnel lining under the combined actions of corrosion degra-dation of preliminary support and creep deformation of surrounding rock. Transportation Geotechnics. 2021; 27: 100501. https://doi.org/10.1016/j.trgeo.2020.100501
8. Guo L, He Y. Optimal control and nonlinear numerical simulation analysis of tunnel rock deformation parameters. Nonlinear Engineering. 2022; 11: 455–462. https://doi.org/10.1515/nleng-2022-0223
9. Zaid M, Sadique MR. The response of rock tunnel when subjected to blast loading: Finite element analysis. Engineering Reports. 2021; 3: e12293. https://doi.org/10.1002/eng2.12293
10. Yang C, Jing W, Daemen JJK, Zhang G, Du C. Analysis of major risks associated with hydrocarbon storage caverns in bedded salt rock. Reliability Engineering and System Safety. 2013; 113: 94–111. https://doi.org/10.1016/j.ress.2012.12.017
11. Chen BR, Zhao XJ, Feng XT, Zhao HB, Wang SY. Time-dependent damage constitutive model for the marble in the Jinping II hydropower station in China. Bulletin of Engineering Geology and the Environment. 2014; 73: 499–515. https://doi.org/10.1007/s10064-013-0542-z
12. Liu HZ, Xie HQ, He JD, Xiao ML, Zhuo L. Nonlinear creep damage constitutive model for soft rocks. Mechanics of Time-Dependent Materials. 2017; 21: 73–96. https://doi.org/10.1007/s11043-016-9319-7
13. Wu F, Zhang H, Zou Q, Li C, Chen J, Gao R. Viscoelastic-plastic damage creep model for salt rock based on fractional derivative theory. Mechanics of Materials. 2020; 150: 103600. https://doi.org/10.1016/j.mechmat.2020.103600
14. Deng H, Zhou H, Li L, Jia W, Wang J. A rock creep model based on Atangana-Baleanu fractional derivative with coupled damage effects of pore water pressure, stress and time. Results in Physics. 2023; 52: 106888. https://doi.org/10.1016/j.rinp.2023.106888
15. Kamdem TC, Richard KG, Béda T. New description of the mechanical creep response of rocks by fractional derivative theory. Applied Mathematical Modelling. 2023; 116: 624-635. https://doi.org/10.1016/j.apm.2022.11.036
16. Yan L, Chang J, Shi W, Wang T, Qiao L, Guo Y, Wang H. Creep deformation characteristics and control technology in deep mine soft rock roadway. Geomechanics and Geophysics for Geo-Energy and Geo-Resources. 2024; 10: 144. https://doi.org/10.1007/s40948-024-00849-8
17. Liang C, Liu J, Yang J, Xu H, Chen Z, Ran L. A creep model for ultra-deep salt rock considering thermal-mechanical damage under triaxial stress conditions. Journal of Rock Mechanics and Geotechnical Engineering. 2024; 16: 588-596. https://doi.org/10.1016/j.jrmge.2023.06.009
18. Frenelus W, Peng H. Evaluating the Time-Dependent Behavior of Deeply Buried Tunnels in Soft Rock Environments and Relevant Measures

Guaranteeing Their Long-Term Stability. Applied Sciences. 2023; 13: 10542. https://doi.org/10.3390/app131810542
19. Sun Y, Pardoen B, Wong HKK. Modelling the creep behaviour and induced failure of clay rock from microscale viscosity to large-scale time-dependant gallery convergences using a multiscale numerical approach. Computers and Geotechnics. 2023; 162: 105691. https://doi.org/10.1016/j.compgeo.2023.105691
20. Paraskevopoulou C, Diederichs M. Analysis of time-dependent deformation in tunnels using the Convergence-Confinement Method. Tunnelling and Underground Space Technology. 2018; 71: 62–80. https://doi.org/10.1016/j.tust.2017.07.001
21. Frenelus W, Peng H, Zhang J. Creep Behavior of Rocks and Its Application to the Long-Term Stability of Deep Rock Tunnels. Applied Sciences. 2022; 12: 8451. https://doi.org/10.3390/app12178451
22. Zhou X, Ju N, Cai J, He C, Wang J, Wang H, Liu R. Damage creep model of viscoelastic rock based on fractional derivative and experimental verification. Frontiers in Environmental Science. 2024; 12: 1338016. https://doi.org/10.3389/fenvs.2024.1338016
23. Li X, Li B, Li X, Yin T, Wang Y, Dang W. Thermal shock effects on the mechanical behavior of granite exposed to dynamic loading. Archives of Civil and Mechanical Engineering. 2020; 20: 66. https://doi.org/10.1007/s43452-020-00070-w
24. Feng YY, Yang XJ, Liu JG, Chen ZQ. A new fractional Nishihara-type model with creep damage considering thermal effect. Engineering Fracture Mechanics. 2021; 242: 107451. https://doi.org/10.1016/j.engfracmech.2020.107451
25. Montero-Cubillo NS, Galindo RA, Olalla C, Muñiz-Ménendez M. Pull-out creep laboratory test for soft rocks. International Journal of Rock Mechanics and Mining Sciences. 2021; 144: 104811. https://doi.org/10.1016/j.ijrmms.2021.104811
26. Duan L, Zhang Y, Lai J. Influence of Ground Temperature on Shotcrete-to-Rock Adhesion in Tunnels. Advances in Materials Science and Engineering. 2019; 2019: 8709087. https://doi.org/10.1155/2019/8709087
27. Martínez-Ibáñez V, Garrido ME, Signes CH, Tomás R. Micro and macro-structural effects of high temperatures in Prada limestone: Key factors for future fire-intervention protocols in Tres Ponts Tunnel (Spain). Construction and Building Materials. 2021; 286: 122960. https://doi.org/10.1016/j.conbuildmat.2021.122960
28. Cao RH, Fang L, Qiu X, Lin H, Li X, Li W. Damage deterioration mechanism and damage constitutive modelling of red sandstone under cyclic thermal-cooling treatments. Archives of Civil and Mechanical Engineering. 2022; 22: 188. https://doi.org/10.1007/s43452-022-00505-6
29. Chen L, Wang CP, Liu JF, Liu YM, Su R, Wang J. A damage-mechanism-based creep model considering temperature effect in granite. Mechanics Research Communications. 2014; 56: 76-82. https://doi.org/10.1016/j.mechrescom.2013.11.009
30. Rouabhi A, Labaune P, Tijani M, Gatelier N, Hévin G. Phenomenological behavior of rock salt: On the influence of laboratory conditions on the dilatancy onset. Journal of Rock Mechanics and Geotechnical Engineering. 2019; 11: 723-738. https://doi.org/10.1016/j.jrmge.2018.12.011
31. Yang SD, Tan WJ, Fang YX. Study on creep mechanical properties and long-term strength of quartz sandstone. Water Power. 2021; 47: 43–50.
32. Wang Y, Wang H, Cui L, Qin N. Investigation and experimental verification of a soft rock creep model at the effect of temperature and confining pressure. Chinese Journal of Applied Mechanics. 2020; 37(6): 06-2561-06.
33. Maranini E, Brignoli M. Creep behaviour of a weak rock: experimental characterization. International Journal of Rock Mechanics and Mining Sciences. 1999; 36(1): 127-138. https://doi.org/10.1016/S0148-9062(98)00171-5
34. Matei A, Cristescu ND. The effect of volumetric strain on elastic parameters for rock salt. Mechanics of Cohesive-frictional Materials. 2000; 5: 113-124. https://doi.org/10.1002/(SICI)1099-1484(200002)5:2<113::AID-CFM84>3.0.CO;2-8
35. Shan RL, Bai Y, Ju Y, Han TY, Dou HY, Li ZL. Study on the Triaxial Unloading Creep Mechanical Properties and Damage Constitutive Model of Red Sandstone Containing a Single Ice-Filled Flaw. Rock Mechanics and Rock Engineering. 2021; 54: 833–855. https://doi.org/10.1007/s00603-020-02274-1
36. Sun L, Lou P, Pan C, Ji P. Mechanical Properties and DEM-Based Simulation of Double-Fractured Sandstone Under Cyclic Loading and Unloading. Sustainability. 2024; 16: 9000. https://doi.org/10.3390/su16209000
37. Kinoshita N, Inada Y. Effects of high temperature on strength, deformation, thermal properties and creep of rocks. Journal of the Society of Materials Science. 2006; 55(5): 489–494. https://doi.org/10.2472/jsms.55.489
38. Tang SB, Yu CY, Heap MJ, Chen PZ, Ren YG. The Influence of Water Saturation on the Short and Long-Term Mechanical Behavior of Red Sandstone. Rock Mechanics and Rock Engineering. 2018; 51: 2669-2687. https://doi.org/10.1007/s00603-018-1492-3
39. Li JD, Gao Y, Yang T, Zhang P, Deng W, Liu F. Effect of water on the rock strength and creep behavior of green mudstone. Geomechanics and Geophysics for Geo-energy and Geo-resources. 2023; 9: 101. https://doi.org/10.1007/s40948-023-00638-9
40. Lin H, Zhang Q, Zhang L, Duan K, Xue T, Fan Q. The Influence of Water Content on the Time-Dependent Mechanical Be-havior of Argillaceous Siltstone. Rock Mechanics and Rock Engineering. 2022; 55: 3939-3957. https://doi.org/10.1007/s00603-022-02826-7
41. Cai X, Zhou Z, Liu K, Du X, Zang, H. Water-Weakening Effects on the Mechanical Behavior of Different Rock Types: Phenomena and Mechanisms. Applied Sciences. 2019; 9: 4450. https://doi.org/10.3390/app9204450
42. Yu C, Tang S, Tang C, Duan D, Zhang Y, Liang Z, Ma K, Ma T. The effect of water on the creep behavior of red sandstone. Engineering Geology. 2019; 253: 64-74. https://doi.org/10.1016/j.enggeo.2019.03.016
43. Hashiba K, Fukui K, Kataoka M, Chu SY. Effect of water on the strength and creep lifetime of andesite. International Journal of Rock Mechanics and Mining Sciences. 2018; 108: 37-42. https://doi.org/10.1016/j.ijrmms.2018.05.006
44. Liu Y, Liu C, Kang Y, Wang D, Ye D. Experimental research on creep properties of limestone under fluid–solid coupling. Environmental Earth Sciences. 2015; 73: 7011–7018. https://doi.org/10.1007/s12665-015-4022-6
45. Zhao B, Wang X, Huang W, Huang T, Liu Y. Experimental study on the long-term stability of shale rock wellbore under high hydraulic pressure. Arabian Journal of Geosciences. 2021; 14: 143. https://doi.org/10.1007/s12517-021-06484-x
46. Li G, Wang Y, Wang D, Wang L, Zhang S, Li C, Teng R. The creep behavior of rock shear seepage under different seep-age-water pressures. Mechanics of Time-Dependent Materials. 2023; 27:351–365. https://doi.org/10.1007/s11043-023-09601-3
47. Huang W, Wang H, Zhang T, He M, Yan L. Hydraulic pressure effect on mechanical properties and permeabilities of layered rock mass: an experimental study. European Journal of Environmental and Civil Engineering. 2020; 27(6): 2422–2433. https://doi.org/10.1080/19648189.2020.1763844
48. Zhang D, Zhang L, Wang Z, Meng F, Wen J, Gao L. Multi-level loading of the seepage pressure in filled cracked sandstone: Seepage-creep mechanical characteristics and crack initiation mechanism. Engineering Fracture Mechanics. 2024; 300: 109991. https://doi.org/10.1016/j.engfracmech.2024.109991
49. Liu D, Yan W, Yan S, Kang Q. Study on the effect of axial and hydraulic pressure coupling on the creep behaviors of sand-stone under multi-loading. Bulletin of Engineering Geology and the Environment. 2021; 80, 6107–6120. https://doi.org/10.1007/s10064-021-02337-9
50. Lv HM. Study on the fractional creep model of roadway filling paste under the coupling effect of pore water pressure and stress. Heliyon. 2024; 10: e35245. https://doi.org/10.1016/j.heliyon.2024.e35245
51. Yang SQ, Jing HW, Cheng L. Influences of pore pressure on short-term and creep mechanical behavior of red sandstone. Engineering Geology. 2014; 179: 10–23. http://dx.doi.org/10.1016/j.enggeo.2014.06.016
52. Gao Y, Wei W, Hua D, Jiang Q. Study on creep characteristics of mudstone with different initial water contents in soaking conditions and its engineering applications. Bulletin of Engineering Geology and the Environment. 2022; 81: 380. https://doi.org/10.1007/s10064-022-02864-z
53. Cheng C, Li X, Li S, Zheng B. Failure Behavior of Granite Affected by Confinement and Water Pressure and Its Influence on the Seepage Behavior by Laboratory Experiments. Materials. 2017; 10: 798. https://doi.org/10.3390/ma10070798
54. Luo Z, Li J, Wang L, Assefa E, Deng H. Study on the Creep Characteristics of Sandstone under Coupled Stress-water Pressure. Periodica Polytechnica Civil Engineering. 2019; 63(4): 1038-1051. https://doi.org/10.3311/PPci.14706
55. Jia CJ, Xu WY, Wang RB, Wang SS, Lin ZN. Experimental investigation on shear creep properties of undisturbed rock dis-continuity in Baihetan Hydropower Station. International Journal of Rock Mechanics and Mining Sciences. 2018; 104, 27-33. https://doi.org/10.1016/j.ijrmms.2018.02.011
56. Damjanac B, Fairhurst, C. Evidence for a Long-Term Strength Threshold in Crystalline Rock. Rock Mechanics and Rock Engineering. 2010; 43: 513-531. https://doi.org/10.1007/s00603-010-0090-9
57. Zhao Y, Zhang L, Wang, W, Wan W, Li S, Ma W, Wang Y. Creep Behavior of Intact and Cracked Limestone Under Multi-Level Loading and Unloading Cycles. Rock Mechanics and Rock Engineering. 2017; 50: 1409-1424. https://doi.org/10.1007/s00603-017-1187-1
58. Cao P, Youdao W, Yixian W, Haiping Y, Bingxiang Y. Study on nonlinear damage creep constitutive model for high-stress soft rock. Environmental Earth Sciences. 2016; 75: 900. https://doi.org/10.1007/s12665-016-5699-x
59. Fabre G, Pellet F. Creep and time-dependent damage in argillaceous rocks. International Journal of Rock Mechanics and Mining Sciences. 2006; 43(6): 950-960. https://doi.org/10.1016/j.ijrmms.2006.02.004
60. Gao Y, Yin D. A full-stage creep model for rocks based on the variable-order fractional calculus. Applied Mathematical Modelling. 2021; 95: 435-446. https://doi.org/10.1016/j.apm.2021.02.020
61. Liu W, Zhang S, Zhao S, Xiang H. Intrinsic model of rock nonconstant damage creep based on fractal-order theory. Applied Mathematical Modelling. 2025; 137: 115681. https://doi.org/10.1016/j.apm.2024.11568
62. Chen W, Konietzky H. Simulation of heterogeneity, creep, damage and lifetime for loaded brittle rocks. Tectonophysics. 2014; 633: 164-175. https://doi.org/10.1016/j.tecto.2014.06.033
63. Yang L, Mei J, Sheng X, Yang W, Li J. Cracking and Creep Behavior of Rocks Considering Propagation and Interaction of Adjacent Cracks Under Hydro-Mechanical Coupling. Rock Mechanics and Rock Engineering. 2021; 54: 4099-4110. https://doi.org/10.1007/s00603-021-02486-z
64. Frenelus W, Peng H, Zhang J. Long-term degradation, damage and fracture in deep rock tunnels: A review on the effect of excavation methods. Fracture and Structural Integrity. 2021; 15(58): 128-150. https://doi.org/10.3221/IGF-ESIS.58.10
65. Wassermann J, Sabroux JC, Pontreau S, Bondiguel S, Guillon S, Richon P, Pili E. Characterization and monitoring of the excavation damaged zone in fractured gneisses of the Roselend tunnel, French Alps. Tectonophysics. 2011, 503: 155–164. https://doi.org/10.1016/j.tecto.2010.10.013
66. Mortazavi A, Molladavoodi H. A numerical investigation of brittle rock damage model in deep underground openings. Engineering Fracture Mechanics. 2012; 90: 101–120. https://doi.org/10.1016/j.engfracmech.2012.04.024
67. Wu Z, Jiang Y, Liu Q, Ma H. Investigation of the excavation damaged zone around deep TBM tunnel using a Voronoi-element based explicit numerical manifold method. International Journal of Rock Mechanics and Mining Sciences. 2018; 112: 158–170. https://doi.org/10.1016/j.ijrmms.2018.10.022

68. Tian M, Han L, Meng Q, Jin Y, Meng L. In situ investigation of the excavation-loose zone in surrounding rocks from mining complex coal seams. Journal of Applied Geophysics 2019; 168: 90-100. https://doi.org/10.1016/j.jappgeo.2019.06.008
69. Do DP, Tran NT, Mai VT, Hoxha D, Vu MN. Time-Dependent Reliability Analysis of Deep Tunnel in the Viscoelastic Burger Rock with Sequential Installation of Liners. Rock Mechanics and Rock Engineering. 2020; 53: 1259-1285. https://doi.org/10.1007/s00603-019-01975-6
70. Lin H, Zhang X, Cao R, Wen Z. Improved nonlinear Burgers shear creep model based on the time-dependent shear strength for rock. Environmental Earth Sciences. 2020; 79: 149. https://doi.org/10.1007/s12665-020-8896-6
71. Li S, Chen C, Zhang F, Yao X. Creep behavior of sandstone containing impact-induced microcracks. Mechanics of Time-Dependent Materials. 2022; 26: 741-760. https://doi.org/10.1007/s11043-021-09510-3
72. Amitrano D. Rupture by damage accumulation in rocks. International Journal of Fracture. 2006; 139: 369-381. https://doi.org/10.1007/s10704-006-0053-z
73. Xu T, Zhou GL, Heap MJ, Zhu WC, Chen CF, Baud P. The Influence of Temperature on Time-Dependent Deformation and Failure in Granite: A Mesoscale Modeling Approach. Rock Mechanics and Rock Engineering. 2017; 50: 2345-2364. https://doi.org/10.1007/s00603-017-1228-9
74. Yang SQ, Hu B, Ranjith PG, Xu P. Multi-Step Loading Creep Behavior of Red Sandstone after Thermal Treatments and a Creep Damage Model. Energies. 2018; 11(1): 212. https://doi.org/10.3390/en11010212
75. Hou R, Zhang K, Tao J, Xue X, Chen Y. A Nonlinear Creep Damage Coupled Model for Rock Considering the Effect of Initial Damage. Rock Mechanics and Rock Engineering. 2017; 52: 1275-1285. https://doi.org/10.1007/s00603-018-1626-7
76. Luo L. Elastic–plastic solutions of reserved deformation for soft rock circular tunnel under high stress. Rock Mechanics Letters. 2025; 2(1): 6. https://doi.org/10.70425/rml.202501.6
77. Kontogianni V, Psimoulis P, Stiros S. What is the contribution of time-dependent deformation in tunnel convergence? Engineering Geology. 2006; 82: 264-267. https://doi.org/10.1016/j.enggeo.2005.11.001
78. Panet M, Sulem J. Convergence-Confinement Method for Tunnel Design, 1st edition, Springer: Gewerbestrasse, Switzerland, 2022; 1-151. https://doi.org/10.1007/978-3-030-93193-3
79. Sulem J, Panet M, Guenot A. Closure analysis in deep tunnels. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts. 1987; 24: 145-154. https://doi.org/10.1016/0148-9062(87)90522-5
80. Audi Y, Jullien A, Dauvergne M, Feraille A, Schwartzentruber LD. Methodology and application for the environmental assessment of underground multimodal tunnels. Transportation Geotechnics. 2020; 24 :100389. https://doi.org/10.1016/j.trgeo.2020.100389
81. Soldo L, Vendramini M, Eusebio A. Tunnels design and geological studies. Tunnelling and Underground Space Technology. 2019; 84: 82–98. https://doi.org/10.1016/j.tust.2018.10.013
82. Frenelus W, Peng H. Towards Long-Term Monitoring of the Structural Health of Deep Rock Tunnels with Remote Sensing Techniques. Fracture and Structural Integrity. 2023; 17(66): 56-87. https://doi.org/10.3221/IGF-ESIS.66.04
83. Frenelus W, Peng H, Zhang J. Seepage Actions and Their Consequences on the Support Scheme of Deep-Buried Tunnels Constructed in Soft Rock Strata. Infrastructures. 2024; 9:13. https://doi.org/10.3390/infrastructures9010013
84. Yang SQ, Peng Xu, Ranjith PG, Chen GF, Jing HW. Evaluation of creep mechanical behavior of deep-buried marble under triaxial cyclic loading. Arabian Journal of Geosciences. 2015; 8: 6567-6582. https://doi.org/10.1007/s12517-014-1708-0
85. Imani M; Walton G; Moradian O; Hedayat A. Monitoring of Primary and Secondary Creep in Granite Using Ultrasonic Monitoring and Digital Image Correlation. ARMA-2023-0337; 57th U.S. Rock Mechanics/Geomechanics Symposium, Atlanta, Georgia, USA, June 2023. https://doi.org/10.56952/ARMA-2023-0337
86. Małkowski P, Niedbalski Z, Majcherczyk T, Bednarek L. Underground monitoring as the best way of roadways support design validation in a long time period. Mining of Mineral Deposits. 2020; 14(3): 1-14. https://doi.org/10.33271/mining14.03.001
87. Buchmayer F, Monsberger CM, Lienhart W. Advantages of tunnel monitoring using distributed fibre optic sensing. Journal of Applied Geodesy. 2021; 15(1):1-12. https://doi.org/10.1515/jag-2019-0065
88. Jeong S, Kim MG, Park J-Y, Oh K-Y. Long-term monitoring method for tunnel structure transformation using a 3D light detection and ranging equipped in a mobile robot. Structural Health Monitoring. 2023; 22(6): 3742-3760. https://doi.org/10.1177/14759217231157237
89. Jiang Q, Zhong S, Pan PZ, Shi Y, Guo H, Kou Y. Observe the temporal evolution of deep tunnel's 3D deformation by 3D laser scanning in the Jinchuan No. 2 Mine. Tunnelling and Underground Space Technology. 2020; 97: 103237. https://doi.org/10.1016/j.tust.2019.103237
90. Zhang QB, He L, Zhu WS. Displacement measurement techniques and numerical verification in 3D geomechanical model tests of an underground cavern group. Tunnelling and Underground Space Technology. 2016; 56: 54–64. https://doi.org/10.1016/j.tust.2016.01.029
91. Leung CKY, Wan KT, Inaudi D, Bao X, Habel W, Zhou Z, Ou J, Ghandehari M, Wu HC, Imai M. (2015). Review: optical fiber sensors for civil engineering Applications. Materials and Structures. 2015; 48: 871–906. https://doi.org/10.1617/s11527-013-0201-7
92. Facchini M, Noether N. Distributed Brillouin Strain and Temperature Sensing in Underground Structures. European Association of Geoscientists & Engineers. EAGE GeoTech 2022 Third EAGE Workshop on Distributed Fibre Optic Sensing, April 2022, 2022: 1-5. https://doi.org/10.3997/2214-4609.20224031
93. Wan X, Li C, Zhao Z, Zhang D, Li Y, Zhang J. Measurements of Excavation Damaged Zone by Using Fiber Bragg Grating Stress Sensors. Sensors. 2021; 21: 5008. https://doi.org/10.3390/s21155008
94. Lin C, Wang X, Nie L, Sun H, Xu Z, Du Y, Liu L. Comprehensive Geophysical Investigation and Analysis of Lining Leakage for Water-Rich Rock Tunnels: A Case Study of Kaiyuan Tunnel, Jinan, China. Geotechnical and Geological Engineering. 2020; 38: 3449-3468. https://doi.org/10.1007/s10706-020-01225-5
95. Wang S, Li L, Cheng S, Yang J, Jin H, Gao S, Wen T. Study on an improved real-time monitoring and fusion prewarning method for water inrush in tunnels. Tunnelling and Underground Space Technology. 2021; 112: 103884. https://doi.org/10.1016/j.tust.2021.103884
96. Yang H, Xu X. Structure monitoring and deformation analysis of tunnel structure. Composite Structures. 2021; 276: 114565. https://doi.org/10.1016/j.compstruct.2021.114565
97. Yang Y, Lai X, Luo T, Yuan K, Li G. Study on creep constitutive model of stratified siltstone and its application to instability analysis in mining. Environmental Earth Sciences. 2022; 81: 270. https://doi.org/10.1007/s12665-022-10390-0
98. Xuyang C, Xufeng W, Dongsheng Z, Dongdong Q, Ya W, Jiyao W, Zechao C. Creep and Control of the Deep Soft Rock Roadway (DSRR): Insights from Laboratory Testing and Practice in Pingdingshan Mining Area. Rock Mechanics and Rock Engineering. 2022; 55: 363-378. https://doi.org/10.1007/s00603-021-02670-1
99. Jiang Q, Qi Y, Wang Z, Zhou C. An extended Nishihara model for the description of three stages of sandstone creep. Geo-physical Journal International. 2013; 193: 841-854. https://doi.org/10.1093/gji/ggt028
100. Innocente J, Paraskevopoulou C, Diederichs MS. Time-Dependent Model for Brittle Rocks Considering the Long-Term Strength Determined from Lab Data. Mining. 2022; 2: 463-486. https://doi.org/10.3390/mining2030025
101. Sainoki A, Tabata S, Mitri HS, Fukuda D, Kodama JI. Time-dependent tunnel deformations in homogeneous and heterogeneous weak rock formations. Computers and Geotechnics. 2017; 92: 186-200. https://doi.org/10.1016/j.compgeo.2017.08.008
102. Cividini A, Contini A, Locatelli L, Gioda G. Investigation on the Cause of Damages of a Deep Tunnel. International Journal of Geomechanics. 2012; 12: 722-731. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000108
103. Satheesh PV, Lohar GK, Kumar A. Analyzing Creep Behavior of Storage Caverns in Weak Rocks. Geotechnical and Geological Engineering. 2024; 42: 4609-4626. https://doi.org/10.1007/s10706-024-02801-9
104. Xia Y, Xiong Z, Dong X, Lu H. Risk Assessment and Decision-Making under Uncertainty in Tunnel and Underground Engineering. Entropy. 2017; 19: 549. https://doi.org/10.3390/e19100549
105. Zhang JZ, Jiang QH, Zhang DM, Huang HW, Liu ZQ. Influence of geological uncertainty and soil spatial variability on tunnel deformation and their importance evaluation. Tunnelling and Underground Space Technology. 2024; 152: 105930. https://doi.org/10.1016/j.tust.2024.105930
106. Tao Y, He W, Sun H, Cai Y, Chen J. Multi-objective optimization-based prediction of excavation-induced tunnel dis-placement. Underground Space. 2022; 7: 735-747. https://doi.org/10.1016/j.undsp.2021.12.005
107. Tarifard A, Török A, Görög P. Fractional Derivative-based Burger Creep Model for Soft Rocks and its Verification Using Tunnel Monitoring Results and Experimental Data. Arabian Journal for Science and Engineering. 2024. https://doi.org/10.1007/s13369-024-09740-w
108. Liu Y, Li Y, Shi X, Ma H, Zhao K, Dong Z, Hou B, Shangguan S. Creep monitoring and parameters inversion methods for rock salt in extremely deep formation. Geoenergy Science and Engineering. 2023; 229: 212092. https://doi.org/10.1016/j.geoen.2023.212092