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# Multi-scale damage correlation mechanism of soft rock under the action of dry-wet cycle

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Research Paper

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## Multi-scale damage correlation mechanism of soft rock under the action of dry-wet cycle

This study proposes a multi-scale damage correlation path to characterise the softening behaviour of soft rock under dry-wet cycles, based on multi-scale damage variables. By testing the mineral composition and internal structural changes of soft rocks under different dry-wet cycles, and based on the energy evolution mechanism and damage constitutive characteristics, the multi-scale correlation effects of soft rock softening under dry-wet cycles were analysed. The results indicate that as the number of dry-wet cycles increase, the mechanical properties of soft rock exhibit an exponential decay mode, and mineral particles exhibit Weibull-distributed random failure behaviour.

**Key words:**

**soft rock, dry-wet cycle, multi-scale damage, energy evolution**

Prethodno priopćenje

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## Mehanizam korelacije višeskalnih oštećenja mekih stijena pod djelovanjem ciklusa sušenja i vlaženja

U ovome radu predlaže se korelacija višeskalnih oštećenja za opis ponašanja mekih stijena pri omekšavanju u ciklusima sušenja i vlaženja, temeljen na varijablama višeskalnih oštećenja. Ispitivanjem mineraloškog sastava i promjena unutarnje strukture mekih stijena nakon različitog broja ciklusa sušenja i vlaženja te na temelju mehanizma evolucije energije i konstitutivnih obilježja oštećenja, analizirani su višeskalni korelacijski učinci omekšavanja mekih stijena. Rezultati pokazuju da s porastom broja ciklusa sušenja i vlaženja mehanička svojstva mekih stijena pokazuju eksponencijalni oblik degradacije, dok mineralne čestice pokazuju nasumično ponašanje loma opisano Weibullovom raspodjelom.

**Ključne riječi:**

**meka stijena, ciklus sušenja i vlaženja, višeskalno oštećenje, evolucija energije**

## 1. Introduction

Soft rocks are rich in clay minerals such as kaolinite and montmorillonite. In complex natural environments, they are often subjected to repeated dry-wet cycles with water. This hydration process leads to the formation of cracks inside the rock, accelerating the degradation of its mechanical properties, and potentially triggering engineering failures. Studying the changes in soft rock under dry-wet cycles can deepen our understanding of the softening mechanisms. These studies are crucial for preventing and controlling geotechnical disasters and effectively developing mineral resources [1-3]. Therefore, this field remains at the forefront of international rock mechanics research.

Based on the above scientific questions, many scholars have conducted in-depth research on soft rocks with different numbers of dry-wet cycles, most of which focus on exploring and analysing the changes in the mechanical properties and structure of soft rocks. In terms of changes in mechanical properties, as the number of dry-wet cycles increased, the compressive strength of the soft rock showed a decreasing trend. The dry-wet cycle of water can increase the structural damage inside soft rocks and cause them to transition from brittle to ductile failure modes [4, 5]. Some researchers have found that the dry-wet cycle of water causes hardening of the soft rock strain. At this point, the soft rock does not have obvious stress peaks or softening characteristics, and the effect of water has a significant impact on the bulk modulus of the soft rock [6-8]. According to the comparative analysis of soft rock before and after the dry-wet cycles, the microcracks and deformation characteristics show significant changes. These changes are mainly achieved through the fractal dimension, CT scanning and nuclear magnetic resonance have been used for quantitative characterisation to reveal the damage mechanism under water–rock interaction [9-12]. In addition, researchers have explored the energy evolution characteristics of soft rock under dry-wet cycles based on energy dissipation and damage constitutive models and established the correlation properties between the damage constitutive model and the entire process of rock deformation and failure. These findings contribute to the estimation of the brittleness characteristics of soft rocks based on damage strain rates [13-15]. Most of these studies focused on the changes in the macroscopic mechanical properties of soft rocks under the action of dry-wet cycles, providing a valuable theoretical basis for the deformation and failure of soft rocks.

Researchers have achieved significant results regarding the internal structural changes in soft rocks through experimental methods. Research has shown that the more dry-wet cycles there are, the looser the particles inside the soft rock, and the more microcracks there are. The complex changes in these internal structures can lead to the gradual deterioration of the mechanical properties of soft rocks [16-18]. When water molecules enter the interior of soft rock, the mineral compositions of water and soft rock undergo chemical changes, and ion exchange occurs between the water and rock. An increase in the number of dry-wet cycles exacerbates the chemical interactions between water and rock and promotes the formation of porous channels within soft rocks [19-21]. Therefore, changes in the microstructure and mineral composition inside soft rock directly affect the contact mode between soft rock particles and ultimately affect the mechanical strength of soft rock. The structural distribution characteristics under different dry-wet cycles can further reveal the deformation and failure laws of soft rocks.

In summary, although extensive research has been conducted on the degradation behaviour of soft rocks under dry-wet cycles, several key issues require further investigation. Most existing studies have focused on the mechanical properties, energy evolution, or constitutive modelling from a single perspective, whereas the intrinsic correlation among the microstructural evolution, energy variation, and constitutive parameters has not been clearly clarified. Therefore, this study integrates micro-scale experiments, energy evolution analysis, and constitutive modelling to systematically analyse the multi-scale damage characteristics of soft rock under different dry-wet cycles and explore the damage amplification effects and their development pathways, thereby providing a more systematic theoretical basis for further research on soft rock engineering disasters.

## 2. Materials and methods

### 2.1. Experimental equipment and rock sample preparation

Siltstone in southern China was selected as the experimental research object to study the mechanical properties and internal structural changes of soft rocks under dry-wet cycles. The main components of this soft rock are quartz and feldspar minerals with a natural density of 2.211 g/cm$^3$. Soft rock samples were collected from deep beneath the surface using a large-diameter drilling machine. The initial soft rock was cut into rock samples using a cutting machine, and a standard cylindrical rock sample suitable for experimental research was prepared indoors with a bottom diameter of 50 mm and height of 100 mm. The equipment used in this experiment included a Matest mechanical testing machine, dry-wet cycle machine, scanning electron microscope (SEM), and X-ray diffractometer (XRD).

### 2.2. Experimental scheme

In the dry-wet cycle test, each specimen was immersed in tap water (pH = 6.8) for 48 h, followed by oven drying at 105 °C for 24 h. After cooling to the standard temperature, the specimen was removed, and this process was defined as one dry-wet cycle. Every variety of rock specimens underwent 0, 1, 3, and 7 instances of both dry-wet cycles.

**Uniaxial examination**

After completion of both wet and dry phases, a uniaxial compression test was conducted. In the uniaxial compression test, the loading technique involved controlling displacement, maintaining a rate of 0.03 mm/min, applying the load vertically until the specimen was destroyed, followed by photographing the damaged rock. In addition, to minimise the effect of specimen variability on the results, three parallel specimens were tested under each condition.

**Examination of Microstructure**

To explore the impact of wet and dry cycles on the internal microstructure of red layer chondrites, a sample was prepared for SEM analysis, capturing microstructure images at 200 magnification following 0, 1, 3, and 7 dry-wet cycles.

**Examination of mineral composition under a microscope**

To explore how wet and dry periods affect the mineral makeup of chondrites, XRD analysis was conducted on the affected rock samples, and their microscopic mineral compositions were determined under 0, 1, 3, and 7 wet and dry conditions). The experimental scheme is shown in Figure 1.

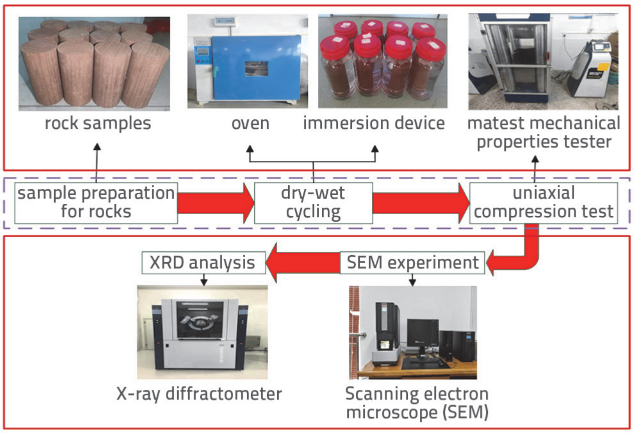

Figure 1. Experimental scheme

## 3. Results

### 3.1. Mechanical properties of soft rocks under the action of dry-wet cycles

As shown in Figure 2, as the number of dry-wet cycles increased, a gradual decline in the peak strength of the chondrites was observed. Specifically, the peak strength of the initial dry rock sample stood at 25.06 MPa, after seven dry-wet cycles, it diminished to 19.77 MPa, marking a notable reduction of 5.29 MPa. This trend was accompanied by a striking alteration in the stress-strain curve. Initially, following zero dry-wet cycles, the post-peak stress of the soft rock plummeted sharply, exhibiting robust brittle behaviour, suggesting superior compaction in the dry state. However, as the number of dry-wet cycles increased, the post-peak stress drop rate decreased, while the post-peak strain increased, indicating a gradual shift from brittle to plastic characteristics. This transition primarily stems from the loosened internal structure of the rock samples resulting from water-rock interactions, which weaken the bonding between mineral particles and lubricate and soften the mineral skeleton.

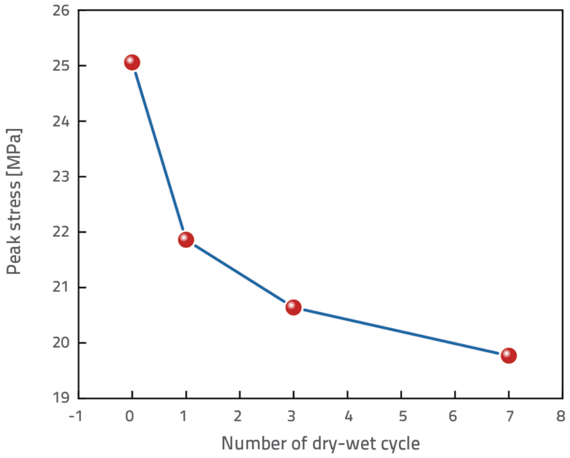

Figure 2. Peak stress of rock samples under different dry-wet cycles

Figure 3 shows the ultimate damage pattern observed in the soft rock after drying and wetting cycles. Under uniaxial compression, the rock samples transitioned from tensile rupture along the axial direction to shear damage as the number of dry-wet cycles increased. This transition was accompanied by a notable increase in the number of cracks within the rock samples, which further interconnected, indicating increasingly severe damage. Notably, the macroscopic cracks observed in the tensile damage were congruently aligned with the principal stress direction.

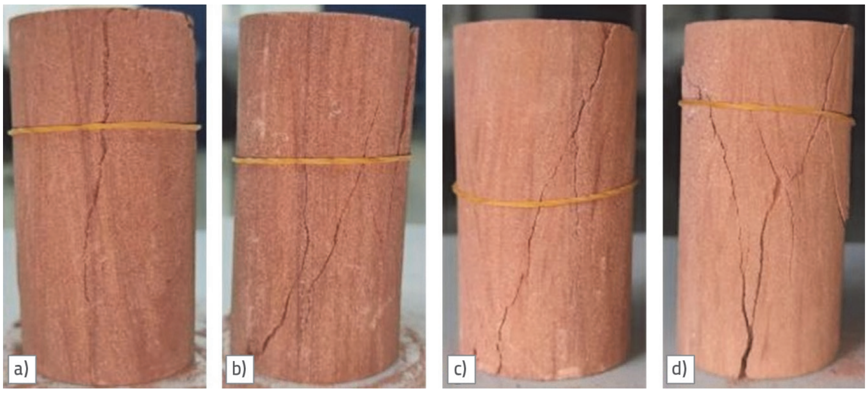

Figure 3. The failure mode of soft rock

### 3.2. Microstructural changes of soft rock under different dry-wet cycles

Figure 4 shows the polarised light microscopy results of the soft rock after the dry-wet cycle. In the natural state (0 dry-wet cycles), the rock sample structure was relatively dense, with a small number of pores evenly distributed and mostly unconnected, and the surface was mostly smooth and straight. After one dry-wet cycle, the particle surface begins to become rough and microcracks form. After three dry-wet cycles, the particles begin to become rounded, the particle boundaries gradually become blurred, and the contact mode between the particles also begins to change. Edge-to-corner contact has started to replace natural face-to-edge and face-to-face modes. Microscopic pores and microcracks developed significantly, providing channels for further water erosion. After seven dry-wet cycles, the particle surface became very rough, with a significant increase in the number of adherent materials. The connecting interface between the mineral particles becomes unclear, and the size and depth of the microscopic pores and microcracks increase significantly.

The mechanism underlying water-induced damage in soft rocks involves two primary facets. First, combined water damage occurs when water molecules infiltrate rock particles through microscopic fissures, forming a polarised water layer that enhances particle mobility and weakens cementation. Second, the damage caused by free water arises because of the presence of numerous microfissures within the rock material. When the rock is loaded in a water-bearing state, the pore water cannot be promptly expelled, leading to a sudden increase in the pressure on the microfissure walls. This pressure increase causes the fissure walls to experience tensile stress, ultimately leading to fissure expansion when the pressure exceeds the ultimate tensile strength. Water molecules concurrently infiltrate the crystal structure, forming hydration films that expand the rock particles and disrupt their particle structure. The combined effects of the initial damage caused by the combined water and superimposed damage from free water contribute significantly to the weakening of the macroscopic mechanical properties of the rock.

### 3.3. Microscopic compositional changes in soft rock under dry-wet cycles

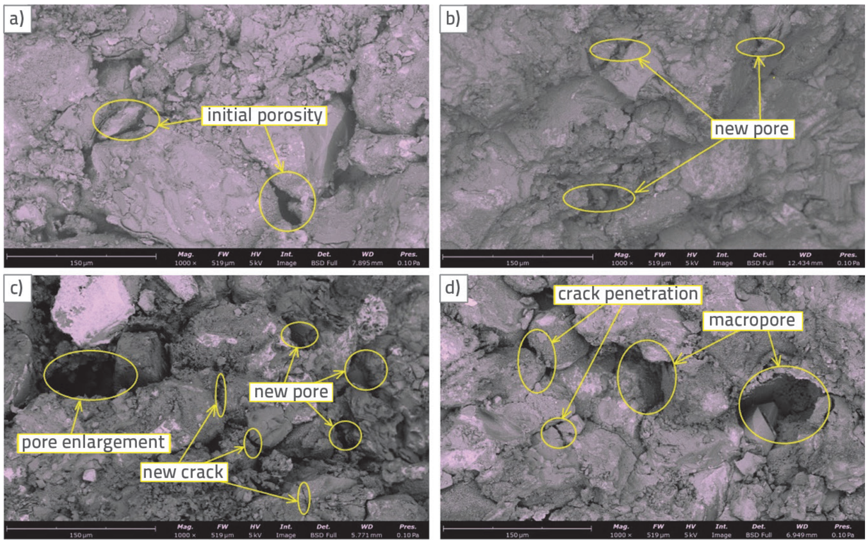

**Figure 4. Polarized light microscopy results after dry-wet cycles: a) 0 dry-wet cycles, b) 1 dry-wet cycle, c) 3dry-wet cycles, d) 7 dry-wet cycles**

XRD testing was performed to analyse the mineral composition of the specimens under different dry-wet cycling conditions. The scanning range was set from 5° to 90° (2θ), with a step size of 0.02° and a scanning speed of 2°/min. The mineral content was calculated using a semi-quantitative analysis method based on the relative peak intensities to obtain the approximate proportions of each mineral phase.

According to the test results listed in Table 1, the samples were mainly composed of detrital and clay minerals. Detrital minerals are dominated by quartz and feldspar, with a minor amount of calcite accounting for approximately 80 % of the total mineral composition, whereas clay minerals, mainly illite and montmorillonite, constitute approximately 20 %. Notably,

**Table 1. The XRD test result of soft rock**

| Minerals | Percentage content of different dry-wet cycles [%] | | | |
|---|---|---|---|---|
| | 0 | 1 | 3 | 7 |
| Quartz | 43.7 | 45.5 | 45.1 | 46.2 |
| Albite | 7.2 | 6.6 | 7.4 | 7.3 |
| Calcite | 7.2 | 7.3 | 7.1 | 7.0 |
| Anorthite | 9.2 | 10.9 | 10.8 | 9.7 |
| K-feldspar | 13.8 | 13.2 | 13.6 | 13.6 |
| Montmorillonite | 2.4 | 1.1 | 0.9 | 1.0 |
| Illite | 16.5 | 15.4 | 15.1 | 15.2 |

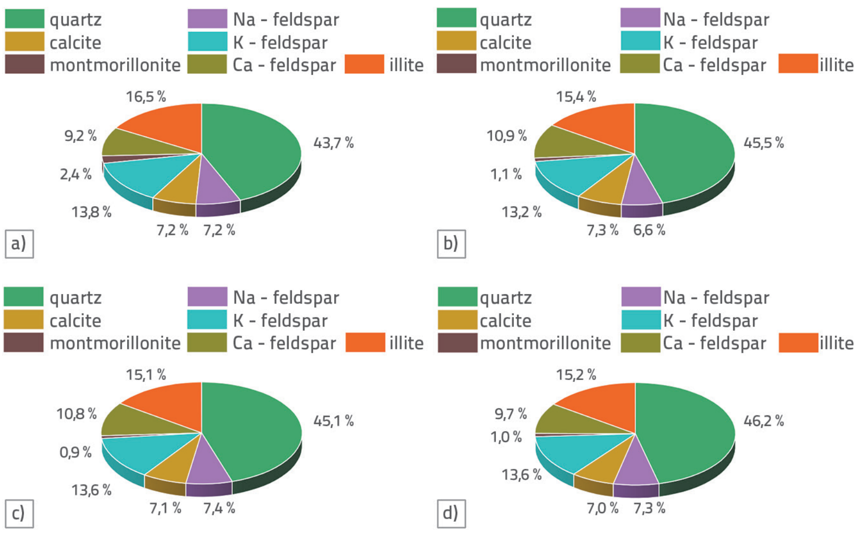

**Figure 5. XRD patterns of rock samples under different dry-wet cycles: a)0 dry-wet cycles, b) 1 dry-wet cycle, c) 3 dry-wet cycles, d) 7dry-wet cycles**

these clay minerals exhibit strong hydrophilicity and tend to undergo volume expansion upon water absorption and contraction during drying, which gradually weakens the bonds between the mineral particles. Under repeated dry-wet cycling, the expansion–contraction behaviour of clay minerals, together with possible slight dissolution effects, can promote the development of pores and microcracks within the rock, leading to structural loosening and degradation of mechanical properties.

A comparative analysis shown in Figure 5.a to 5.d reveals a reduction in the clay mineral content following dry-wet cycles. This decrease was attributed to the swelling and softening of clay minerals, such as illite and montmorillonite, when exposed to water during cycling. In contrast, changes in the other mineral components were relatively insignificant. This can be explained by the fact that under the influence of dry-wet cycles, these minerals may undergo minor variations in content due to chemical reactions such as dissolution and hydrolysis. Overall, the variations in the contents of the individual mineral components were all less than 3 %, indicating no significant change in the mineral composition. This indicates that the degradation of mechanical properties under dry-wet cycling is mainly related to the development of pores and microcracks and the alteration of particle contact conditions rather than to substantial changes in mineral composition, which is consistent with the SEM observations.

## 4. Damage constitutive eqution and discussion

### 4.1. Energy evolution law of rock samples under dry-wet cycles

In the context of uniaxial compression, the emergence and propagation of macroscopic cracks within rocks are often observed along with crack penetration. As the external loading progressed, the strain energy accumulated in the rock gradually dissipated, resulting in a notable shift in the relationship between the elastic strain energy ($U^e$) and dissipated strain energy ($U^d$) during the loading and damage processes of the rock. Based on the fundamental precepts of the first law of thermodynamics, we can deduce that the mechanical force exerted by the machinery during the loading process of the rock sample is translated into strain energy ($U$) within the rock itself.

$$W = U = U^e + U^d \tag{1}$$

Under uniaxial compression, the lateral pressure is $\sigma_2 = \sigma_3 = 0$. Therefore, the strain energies inside the soft rock are as follows:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 \tag{2}$$

$$U^e = \frac{1}{2E_i}\left[\sigma_1^2 + 2\sigma_3^2 - 2\mu(\sigma_3^2 + 2\sigma_1\sigma_3)\right] = \frac{\sigma_1^2}{2E_0} \tag{3}$$

In the formula above, μ is Poisson's ratio, $E_i$ is the unloaded modulus of elasticity of the rock, which can be replaced by the initial modulus of elasticity $E_0$ in the calculation. Rock damage involves the generation, extension, and penetration of cracks in a sequence inherently coupled with the accumulation, dissipation, and release of energy. Figure 6 provides a visual illustration of the energy evolution characteristics exhibited by the specimens during the entire uniaxial compression process under varying numbers of dry-wet cycles.

As shown in Figure 6, the energy evolution of soft rock subjected to varying dry-wet cycles manifests in four distinct stages.

**Stage I:** As the stress increases, microcracks and pores within the rock gradually close, signalling the transition into the elastic phase. During this phase, the stored elastic energy exceeds the dissipated energy.

**Stage II:** This stage aligns with the macroscopic energy evolution of soft rock, commencing from the completion of compaction to the onset of macroscopic crack formation. During this phase, the external energy input is primarily converted into elastic strain energy storage. As microscopic cracks gradually emerged within the rock, a portion of the input energy was consumed, leading to a gradual yet steady increase in the dissipated energy.

**Stage III:** This stage corresponds to the transition from crack initiation to peak strength in the stress-strain curve. Here, the dissipated energy underwent a significant stepwise increase,

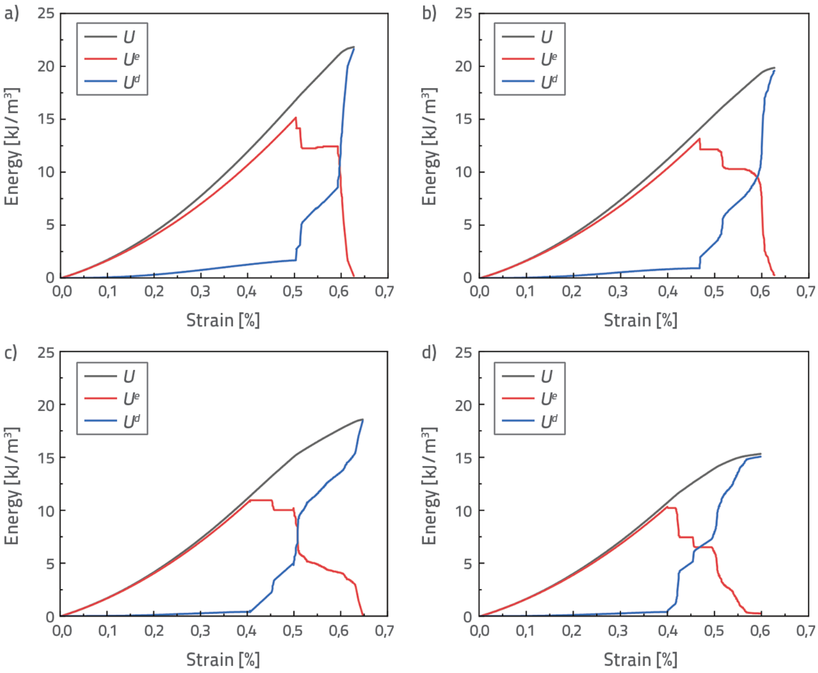

**Figure 6. Energy evolution curve of rock samples under different dry-wet cycles: a) 0 dry-wet cycles, b) 1 dry-wet cycle, c) 3 dry-wet cycles, d) 7 dry-wet cycles**

indicating a gradual increase in the proportion of external input energy being dissipated.

**Stage IV:** corresponds to the post-peak phase of the stress-strain curve. Upon reaching the peak strength, the specimen underwent catastrophic failure, leading to a massive and abrupt release of stored elastic strain energy. This release resulted in a sharp decline in the elastic strain energy, whereas the dissipated energy accumulated rapidly. However, with increasing dry-wet cycles, the rate of the post-peak dissipation energy decline decreased, accompanied by an increase in the post-peak strain. This observation suggests a gradual transition from brittle to plastic characteristics in the chondrites, highlighting the impact of dry-wet cycles on their deformation and failure behaviour.

Table 2 presents the variation in the energy parameters of the specimens at the peak strength under different numbers of dry-wet cycles. With an increase in the number of cycles, both the input strain energy and elastic strain energy showed a clear decreasing trend, indicating a gradual reduction in the energy storage capacity and stiffness of the specimens. In contrast, the dissipative strain energy remained relatively low, with only slight fluctuations. These results demonstrate that repeated dry-wet cycling reduces the ability of the specimens to accumulate elastic energy, reflecting the progressive deterioration of their mechanical properties.

## 4.2. Constitutive equation for the degradation and damage of soft rock under dry-wet cycles

The Lemaitre strain equivalence hypothesis suggests that rock materials are strain equivalent before and after deformation. Based on this, the principal relationship of the rock damage was established.

$$\sigma^* = E\varepsilon\,(1 - D) \tag{4}$$

In the equation (4), $\sigma^*$ is the effective stress, $E$ is the modulus of elasticity, $\varepsilon$ is the strain and $D$ is the damage variable. Assuming that the rock is an isotropic material and the microelement strength parameter $F$ satisfies the Weibull distribution, the probability density function of the microelement strength of the rock material can be expressed as follows:

$$P(F) = \frac{m}{F_0}\left(\frac{F}{F_0}\right)^{m-1}\exp\left[-\left(\frac{F}{F_0}\right)^{m}\right] \tag{5}$$

In the equation (4), $m$ and $F_0$ are the Weibull scale parameter and shape parameter, respectively. The Drucker-Peage damage criterion was chosen as the criterion for judging the damage to micrometamorphic bodies.

$$F = \frac{\sqrt{3}E\varepsilon_1}{3(\sigma_1 - 2\mu\sigma_3)}\left[\frac{\sin\phi(\sigma_1 + 2\mu\sigma_3)}{\sqrt{3+\sin^2\phi}} + \sigma_1 - \sigma_3\right] \tag{6}$$

**Table 2. Energy parameters of specimens under different dry-wet cycles**

| **Number of dry-wet cycles** | **Strain energy** [kJ/m³] | **Elastic strain energy** [kJ/m³] | **Dissipative strain energy** [kJ/m³] |
|---|---|---|---|
| 0 | 16.83 | 15.15 | 1.67 |
| 1 | 14.07 | 13.16 | 0.92 |
| 3 | 11.33 | 10.95 | 0.38 |
| 7 | 10.73 | 10.33 | 0.40 |

**Table 3. Parameters and calculation results**

| Parameters | Number of dry-wet cycle | | | |
|---|---|---|---|---|
| | 0 | 1 | 3 | 7 |
| $m_1$ [GPa] | 4.36 | 3.86 | 3.5 | 3.42 |
| $M_2$ [GPa] | 19.10 | 15.63 | 7.78 | 7.55 |
| $R^2$ | 0.9 | 0.9 | 0.9 | 0.9 |

In Equation (6), $\sigma_1$ and $\sigma_3$ are the first and third principal stress, $\varepsilon_1$ is the first principal strain, and $\varphi$ is the internal friction angle. After substituting Equation (6) into Equation (5), the rock damage variable *D* was obtained.

$$D = \exp\left\{-\frac{F}{F_0}\right\}^m \tag{7}$$

Substituting Equation (7) into Equation (4) under uniaxial compression conditions, the rock damage constitutive equation is expressed as

$$\sigma = E\varepsilon\,(1 - D) \tag{8}$$

It is assumed that the internal pores of soft rock under different dry-wet cycles are randomly distributed, therefore, the change rule of the stress-strain curve is closely related to parameters *m*, $F_0$ and *F*. Under the condition of fully considering the influence of the damage stage on the damage constitutive model, Equation (8) can be reformulated as follows:

$$\sigma = E\varepsilon\left\{1 - \exp\left[-\left(\frac{F}{F_0}\right)^m\right]\right\} \tag{9}$$

Taking the logarithms on both sides of Equation (9), it is expressed as

$$\ln\,[\ln E\varepsilon - \ln(E\varepsilon - \sigma)] = m \cdot \ln F - m \cdot \ln F_0 \tag{10}$$

Equation (10) shows that the constitutive equation contains numerous unknown parameters. In order to obtain the theoretical solution of the damage eigenstructure equation, the method reported in the reference was adopted.

Let $y = \ln\,[\ln E\varepsilon - \ln(E\varepsilon - \sigma)]$; $x = \ln F - \ln F_0$., substituting the hypothetical function *x* and *y* into equation (10), it is expressed as:

$$y = m \cdot x \tag{11}$$

Equation (11) shows that $y$ is a primary linear function of *x*, and the value of *m* is a parameter variable associated with different dry-wet cycles. The plastic deformation stage is regarded as the elastic stage. Assuming that the dividing stress between the elastic stage and the destructive stage of the stress-strain curve of the chondritic rock is $\sigma_d$, the expressions corresponding to $\sigma < \sigma_d$ stage and $\sigma > \sigma_d$ stage of the stress-strain curve are as follows:

$$\begin{cases} y_1 = m_1 x_1 (\sigma < \sigma_d) \\ y_2 = m_2 x_2 (\sigma \geq \sigma_d) \end{cases} \tag{12}$$

The values of the parameter variable $m_i$ associated with different dry-wet cycle intensities can be obtained by numerically fitting the stress-strain curves using Equation (12). $m_1$ and $m_2$ represent the parameter variables for the compaction and elastic stages, respectively. Based on the above analysis, the segmental fitting of the stress-strain curves using Equation (12) yielded the value of *m*. The results are summarised in Table 3.

According to Table 2 and Table 3, with the increase in the number of dry-wet cycles, the Weibull parameters $m_1$ and $m_2$ exhibit a clear decreasing trend: $m_1$ decreases from 4.36 to 3.42, and $m_2$ decreases from 19.10 to 7.55. Meanwhile, the input strain energy decreases from 16.83 kJ/m³ to 10.73 kJ/m³ and the elastic strain energy decreases from 15.15 kJ/m³ to 10.33 kJ/m³ indicating that the energy storage capacity and stiffness of the specimens continuously weaken with increasing cycle numbers. The reduction of parameter $m_1$ corresponds well to the decreasing trend of elastic strain energy, reflecting the degradation of stiffness and load-bearing capacity in the pre-peak stage, while the decrease of $m_2$ is related to the change in damage evolution behaviour in the post-peak stage. Overall, the evolution of the parameters shows good consistency with the variation in energy characteristics, and can, to a certain extent, characterise the overall features of elastic modulus degradation and damage development of the specimens under dry-wet cycling.

## 4.3. Multi-scale correlation characteristics of soft rock damage and failure

As shown in Figure 7, soft rocks under dry-wet cycles exhibited multi-scale damage-correlation properties. When water molecules penetrate soft rock particles through microscopic cracks, hydration occurs between the water and rock, weakening the connections between the particles. When the loading of soft rock is in a water-containing state, pore water cannot be discharged in a timely manner, resulting in a sudden increase in the pressure on the microfracture wall. An increase in pressure causes tensile stress in the cracked wall, ultimately leading to crack expansion when the pressure exceeds the ultimate tensile strength. Simultaneously, water molecules penetrate the crystal structure, forming a hydration film that causes soft rock particles to expand and disrupt their particle structure.

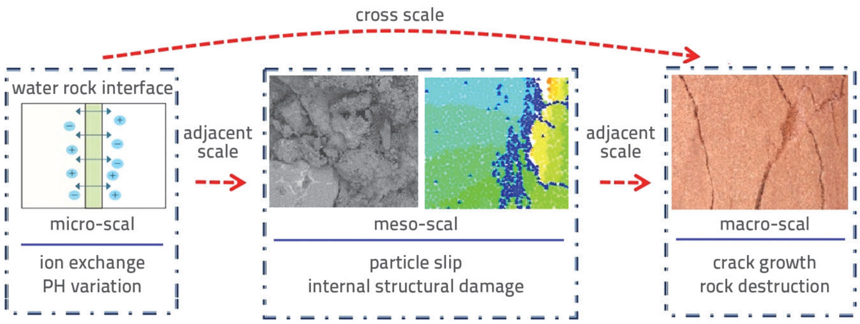

**Figure 7. Multi-scale intrinsic correlation damage attributes of soft rock**

The combined effect of the initial damage caused by water and the cumulative damage caused by free water significantly weakens the macroscopic mechanical properties of soft rock.

### 4.4. Discussion

In terms of quantitative results, the attenuation amplitudes of the peak strength and elastic modulus with increasing dry-wet cycles in this study were generally consistent with the trends reported in the literature. For example, Yu et al. [22] reported a similar exponential decay trend, whereas Cratchev et al. [23] observed a slightly larger reduction in strength, which may be related to the differences in the solution type, testing methods, and lithological characteristics. Wen et al. [24] and Yin et al. [25] modelled the degradation process based on the Weibull or energy damage theories, and the evolution characteristics of their model parameters showed good agreement with the variation trends of $m_1$ and $m_2$ in the present study. It should be noted that the aforementioned studies mainly focused on analysis from a single perspective, such as mechanical properties, energy evolution, or constitutive modelling. In contrast, this study comprehensively considers the intrinsic relationships among microstructural evolution, changes in energy partitioning, and variations in constitutive parameters within a unified experimental framework, thereby providing a more systematic interpretation of the damage mechanism of soft rock under dry-wet cycling.

## 5. Conclusions

Macroscopically, with an increase in the number of dry-wet cycles, the strength, elastic modulus, and elastic strain energy of the soft rock exhibited an exponential decay pattern. The rock samples gradually transitioned from brittle to plastic, shifting from tensile fracture failure along the axial direction to shear failure with an increasing degree of damage.

Mesoscopically, as the number of dry-wet cycles increases, the particle surfaces of the soft rock become significantly rougher, and the attached materials noticeably multiply. The interfaces between the mineral particles became indistinct, and the size and depth of the mesopores and microcracks increased remarkably. Crack propagation was observed, accompanied by bulk shedding and uneven distribution. Consequently, the rock samples transitioned into a loose and porous structure.

By calculating the constitutive model parameters $m_1$ and $m_2$ for the damage to soft rock under the influence of dry-wet cycles, it was found that the change in parameter m1 can reflect the variation in its strength and elastic modulus well. Specifically, the lower the value of $m_1$, the lower are the strength and elastic modulus. Meanwhile, the change in the parameter $m_2$ can effectively reflect the failure mode of the rocks, with a smaller absolute value of $m_2$ indicating more pronounced plastic properties. This research outcome provides a valuable reference for understanding the damaging effect of dry-wet cycles on soft rock.

## Acknowledgements

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## REFERENCE

[1] Hamilton McMillan, R., Eberhardt, E., Ryan Campbell, R., Primadiansyah, A.: Monitoring stress-induced brittle rock mass damage for preventative support maintenance, International Journal of Rock Mechanics and Mining Sciences, 183 (2024), 105927, https://doi.org/10.1016/J.IJRMMS.2024.105927

[2] Kovačević, M.S., Bačić, M., Arapov, I.: Prospects of underground engineering in the use of shallow geothermal energy, GRAĐEVINAR, 64 (2012) 12, pp. 1019-1028, doi: https://doi.org/10.14256/JCE.663.2012

[3] Stubbs, A.R., Power, L.M., Paulo, C., Wang, B.L., Zeyen, N., Wilson, S., Mervine, E., Gunning, C.: Impact of wet-dry cycles on enhanced rock weathering of brucite, wollastonite, serpentinite and kimberlite: Implications for carbon verification, Chemical Geology, 637 (2023), 121674, https://doi.org/10.1016/J.CHEMGEO.2023.121674

[4] Liu, J., Qiu, X.Y., Yu, X.W., Zeng, L., Fu, H.Y.: Wetting Deformation and Constitutive Modeling of Predisintegrated Carbonaceous Mudstone Subjected to Drying-Wetting Cycles, International Journal of Geomechanics, 25 (2024) 2, 9745, https://doi.org/10.1061/IJGNAI.GMENG-9745

[5] Wang, G.L., Zhang, T.Y., Zhang, L.: The law of strength damage and deterioration of jointed sandstone after dry-wet cycles, Journal of Mountain Science, 20 (2023) 4, pp. 1170-1182, https://doi.org/10.1007/S11629-022-7605-1

[6] Knez, D., Khalilidermani, M., Zamani, M.A.M.: Water Influence on the Determination of the Rock Matrix Bulk Modulus in Reservoir Engineering and Rock-Fluid Coupling Projects, Energies, 16 (2023) 4, 1769, https://doi.org/10.3390/EN16041769

[7] Liu, X.C., Huang, F., Zheng, A., Hu, X.T.: Micro-dissolution mechanism and macro-mechanical behavior of red-bed soft rock under dry-wet cycle, Materials Letters, 362 (2024), 136220, https://doi.org/10.1016/J.MATLET.2024.136220

[8] Tomanović, Z.: The stress and time dependent behaviour of soft rocks, GRAĐEVINAR, 64 (2012) 12, pp. 993-1007, doi: https://doi.org/10.14256/JCE.815.2012

[9] Qi, S.X., Zhang, H.L., Bian, H.B., Wang, J.J., Xu, S.X., Wu, B.: Damage Characteristics and Degradation Mechanism of Silty Mudstone Under Wet-Dry Cycling, Geotechnical and Geological Engineering, 42 (2024) 7, pp. 6095-6112, https://doi.org/10.1007/S10706-024-02877-3

[10] Yu, F., Tong, K.W., Fu, Z.H., Feng, G.S., Zhou, Z., Chen, S.X., Dai, Z.J.: Multi-scale deformation characteristics and mechanism of red-bed mudstone in dry-wet environment, Frontiers in Earth Science, 10 (2022), 974707, https://doi.org/10.3389/FEART.2022.974707

[11] Zhao, Y.F., Ren, S., Jiang, D.Y., Liu, R., Wu, J.X., Jiang X.: Influence of wetting-drying cycles on the pore structure and mechanical properties of mudstone from Simian Mountain, Construction and Building Materials, 191 (2018), 923-931, https://doi.org/10.1016/j.conbuildmat.2018.10.069

[12] Gratchev, I., Pathiranagei, S.V., Kim, D.H.: Strength properties of fresh and weathered rocks subjected to wetting-drying cycles, Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 5 (2019) 3, pp. 211-221, https://doi.org/10.1007/s40948-019-00104-5

[13] Wen, T., Wang, Y.K., Tang, H.M., Zhang, J.R., Hu, M.Y.: Damage Evolution and Failure Mechanism of Red-Bed Rock under Drying-Wetting Cycles, Water, 15 (2023) 15, 2684, https://doi.org/10.3390/W15152684

[14] Huang, Z., Zhang, W., Zhang, H., Zhang, J.B., Hu Z.J.: Damage characteristics and new constitutive model of sandstone under wet-dry cycles, Journal of Mountain Science, 19 (2022) 7, pp. 2111-2125, https://doi.org/10.1007/S11629-021-7239-8

[1] Deng, J.H., Chen, C., Wu, X.N.: The influence of loading rate on the mechanical behavior and energy evolution characteristics of hard and soft rock under triaxial compression, Journal of Theoretical and Applied Mechanics, 60 (2022) 3, pp. 495-508, https://doi.org/10.15632/jtam-pl/151819

[16] Ma, T.F., Liu, H.H., Zou, Q.L., Kong, F.J., Ran, Q.C., Wang, P.T.: Damage evolution characteristics and deterioration mechanism of mechanical properties of sandstone subjected to drying-wetting cycles, Journal of Materials Research and Technology, 23 (2023), pp. 4591-4605, https://doi.org/10.1016/J.JMRT.2023.02.068

[17] Ying, P., Zhu, Z.M., Ren, L., Deng, S., Niu, C.Y., Wan, D.Y., Wang F.: Deterioration of dynamic fracture characteristics, tensile strength and elastic modulus of tight sandstone under dry-wet cycles, Theoretical and Applied Fracture Mechanics, 109 (2020), 102698, https://doi.org/10.1016/j.tafmec.2020.102698

[18] Liu, X.C., Huang, F., Zheng, A.C., Hu, X.T.: Microscopic simulation of mechanical tests on red-bed soft rock based on the evolutionary law of mineral composition under dry-wet cycles, Materials Today Communications, 40 (2024), 110000, https://doi.org/10.1016/J.MTCOMM.2024.110000

[19] Mohamed, A., Asmoay, A., Alshehri, F., Abdelrady, A., Othman A.: Hydro-Geochemical Applications and Multivariate Analysis to Assess the Water-Rock Interaction in Arid Environments, Applied Sciences, 12 (2022) 13, 6340, https://doi.org/10.3390/APP12136340

[20] Zhang, L., Wang, G.L., Wang, R.Q., Liu, B.L., Wang, K.: The Mesoscopic Damage Mechanism of Jointed Sandstone Subjected to the Action of Dry-Wet Alternating Cycles, Applied Sciences, 14 (2024) 22, 10346, https://doi.org/10.3390/APP142210346

[21] Li, S.N., Huang, Z.H., Liang, Q., Liu, J., Luo, S.L., Zhou, W.Q.: Evolution Mechanism of Mesocrack and Macrocrack Propagation in Carbonaceous Mudstone under the Action of Dry-Wet Cycles, Geofluids, 2022 (2022), 6768370, https://doi.org/10.1155/2022/6768370

[22] Yu, X.W., Fu, H.Y, Zeng, L, Zhang, G.J, Zhang, H.G., Liu, N.: Cracking of silty mudstone subjected to wetting-drying cycles, Journal of Rock Mechanics and Geotechnical Engineering, (2025) 17:4195-4210. doi: 10.1016/j.jrmge.2024.10.009

[23] Wen, T., Wang, Y.K., Tang, H.M., Zhang, J.L.: Damage Evolution and Failure Mechanism of Red-Bed Rock under Drying-Wetting Cycles, Water, (2023) 15:2684. https://doi.org/10.3390/w15152684

[24] Yin, X.M., Wang, L.N., Liu, W.L.: The damage and deterioration effects of dry-wet cycles on impurity-bearing gypsum rock and a fractal damage constitutive model, Fatigue Fract Eng Mat Struct, (2025) 48:2599-2617. https://doi.org/10.1111/ffe.14628