Characterization and Modeling Study on Softening and Seepage Behavior of Weakly Cemented Sandy Mudstone After Water Injection

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Characterization and modeling study on softening and seepage behavior of weakly cemented sandy mudstone after water injection

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Abstract Water injection induced rock softening and the associated water seepage characteristics are the common and basic problems in hard roof pressure relief, underground reservoir construction and the prevention of mine water disaster. In this paper, a series of laboratory studies was carried out to investigate these characteristics with the weakly cemented sandy mudstone collected from Shendong Buertai coal mine, China. The characteristics of water softening and the stress-seepage interactions in saturated weakly cemented sandy mudstone were directly obtained. Then a modification method of the constitutive model for rock mass considering the softening effect and a stress-damage-driven model for permeability evolution were established. Research results show that water saturation reduces the tensile strength, compressive strength and cohesion by 56%, and reduces the elastic modulus by 28%. The hydraulic effect on Poisson’s ratio and internal friction angle is negligible. The relationship between the permeability of weakly cemented sandy mudstone with complete compaction deformation is to be divided into three stages of seepage shielding, seepage surge and seepage recovery. Rock permeability in each stage has a negative exponential relationship with the effective stress. This research provides a theoretical basis for the researches of hydro-mechanical couplings on weakly cemented sandy mudstone, which is insightful for rock engineering practice.
Keywords: weakly cemented rock • hydro-mechanical interaction • softening and seepage behavior • constitutive model • permeability model

1 Introduction

Shendong coal mining area spanning three provinces of shaanxi, Mongolia and Shanxi, is now the largest mining area of coal mine in China, among which Buertai coal mine is the largest mining area in the world. The host rock of Shendong coal mining area mainly consists of sandstone and sandy mudstone (Gu et al. 2015; Jarvis et al. 2018; Song et al. 2020). In general, these rocks are weakly cemented and the softening effects under water saturation are significant (Li et al. 2016; Du et al. 2019). Water injection and hydraulic fracturing into the main roof can effectively manage the stress and reduce the probability of bursting events. For example, the hard roof at Buertai coal mine 42108 longwall face was softened and fractured by water injection and fracturing. As a result, the length and magnitude of periodic weighting reduced 18.9% ~ 70.6% and 13.7% ~ 19.4%, respectively (Yang et al. 2020). On the other hand, it is critical to understand the dynamic stability of underground structure under hydro-mechanical coupling effect. This is because protection of groundwater has the highest priority at Shendong mining area (Selene et al. 2020). In addition, rock engineering associated with tunnels, water conservancy and underground chambers in western China also encounter varying degrees of water softening and seepage problems. Therefore, it is of great importance to study the hydraulic effects and seepage characteristics of weakly cemented rocks in Shendong coal mining area.

The physical and mechanical properties of weakly cemented rocks in western China can change substantially when saturated. A series of researchers has carried out experiments and mechanism studies on the water softening effect of weakly cemented rocks (Goodarzia et al. 2021). Under the coupled hydro-mechanical conditions, the initial unloading state promotes the nucleation of the secondary cracks at the low internal hydraulic pressures, whereas the nucleation of secondary cracks is inhibited when the hydraulic pressure of the fluid-injection is high.
It is suggested that retaining a high initial water content in crushed mudstone can maintain its stability of the shear stress. During creep immersion, the increment in the creep-shear displacement increases as the creep-stress ratio increases, and the initial water content decrease. Under the same density, the peak shear strength decreases with an increase in the increment of the creep-shear displacement (Sawatsubashi et al. 2021). Experiments of complete stress-strain curves under natural condition and water saturated condition indicate that the peak strength decreases by 21.6% and 17.3% respectively when test block reacts with water in elastic and plastic stage, but residual strength decreases by 4.1%, 33.8%, 9.6% and 55.9% during elastic, plastic, strain-softening and residual stage under action of water. Overall, the mudstone roofs containing high water absorption capacity minerals makes it disintegrate easily and expand strongly, another aspect is that its peak strength and residual strength decrease after reacting with water, which is the instability mechanism of mudstone roofs (Yao et al. 2005). Water saturation changes the mesoscopic mechanism of rock spalling through true-triaxial compression tests. The mechanisms of water on rockburst prevention are to reduce residual elastic strain energy, avoid excessive concentration of strain energy, and increase rockburst resistance. The ratio of the far-field maximum principal stress to the uniaxial compressive strength can be used as an index to evaluate the stability of hard-rock tunnels (Luo et al. 2020). Liu et al. (2020) discussed the influence of saturation on the strength parameters, deformation characteristics and energy evolution of the mudstone at Badong formation. Based on the findings, they proposed a relationship between mechanical properties, energy evolution and microcrack development. The results are insightful for the water-bearing weak cemented rock mass in Shendong coal mining area.

The seepage of water in the fractured rock mass results in the change of water content within the rock, which in turn leads to the hydro-mechanical interactions. After water injection, more pores with diameter larger than 10 nm are formed that would improve the transport capacity of gas in pores (Song et al. 2018). The changes of porosity and permeability are obvious in the carbonate rock after low salinity water injection, and it is important in
the near injection area (Ali et al. 2020). Water pressure in pore and seepage flow can macroscopically characterize the seepage situation of the rock formation and the change of pore pressure generally goes through five stages of the initial constant stage, increase phase, peak fluctuation phase, decay phase and stable phase (Wen et al. 2021). Robert et al. (2017) found that during a vertical loading and unloading cycle, hysteresis in flow was observed signifying the importance of stress history on fracture flow. The pore water pressure decreases by increasing the permeability, but the changes in pore water pressure distribution become negligible once the magnitude of permeability is above $10^{-8}$ m/s (Shaghaghi, et al. 2020). The permeability evolution in triaxial compression test after the sample failure increases up to two orders of magnitude for mudstone, while the permeability for gypsum does not increase and the final permeability is even lower than the initial permeability due to the different failure modes (Wu, et al. 2021). Flow properties of fault in mudstone may be able to be estimated from stress condition and a yield criterion of the host rock (Uehara, et al. 2014). Grain size distribution and mineralogical composition control the vertical permeability, the compaction trends of pure quartz and quartz-smectite 15:85 mixtures describe the maximum and minimum boundaries, respectively (Mohammad, et al. 2019). For concrete, it is determined that the measurement methods significantly affects the density, porosity, and permeability values. When the size of aggregate and mixture ratios are ignored, the coefficient of constant head permeability tests is found to be 75% of the coefficient of falling head permeability tests, on average (Ahmet, et al. 2021). When the flow is laminar and the Reynolds number is small enough (<10), fluid flow depends on the discontinuity between the pressure in solid and in liquid, and the permeability depends on the porosity and specific surface area of pores and cracks (Sibiryakov, et al. 2021).

At present, the coal mining disaster prevention and control, and underground space excavation at the Buertai Mine in Shendong mining area have experienced hydro-mechanical coupling and water seepage problems. However, the systematic research on this issue is still limited. Based on the weakly cemented sandy mudstone in Shendong coal mining area, this paper studies common issues such as rock mechanics, water softening effect and
water seepage through experiments. Such investigations include experiments on rock saturation process, uniaxial compression, triaxial compression, Brazilian splitting and seepage test. The research results can effectively enrich the fundamental theory of rock mechanics and provide guidance for related engineering practice.

2 Analysis of rock saturation characteristics

Rock samples used in the test were cored from Buertai coal mine, Shendong mining area, China. The mining seam has a sandy mudstone roof with a depth of about 450 meters, and the density of the sandy mudstone is approximately 2.44 g/cm$^3$. The coring site can be seen in Fig. 1.

Prior to the test, part of the rock samples were dried under 105 °C for 24 h. After natural cooling, they were soaked in water until fully saturated. Because the sandy mudstone is weakly cemented, some samples disintegrated during the saturation process. Figure 2 shows the saturation curves of the dry rock samples for the experiment. It can be seen that the saturation rate of the rock sample gradually slows with time. The saturation process mainly occurred within the first six hours after immersion; and the water content does not change much in the subsequent 18 hours. The saturated sandy mudstone samples used in this experiment are immersed for about 24 hours. In this study, the time effects of water saturation on natural and saturated rock samples are not considered. Based on the results, it is clear that the sandy mudstone used in the test has a natural water content of 1.3% and an average saturated water content of 5.06%.
3 Water softening effect and modification of constitutive model

3.1 Laboratory tests

The collected rock cores are shaping into two kinds of geometries. The first type of rock samples was cut as cylindrical samples with a diameter of about 50 mm and a height of 100 mm, which were used for compression and permeability tests. The other type was prepared as disc samples with a diameter of about 50 mm and a height...
of 25 mm that were suitable for the Brazilian test. The parallelism of the upper and lower ends and the flatness of
the faces were both less than 0.02.

Figure 3a shows a servo-controlled stress-seepage-temperature-chemical (MHTC) coupling system at China
University of Mining and Technology-Beijing, which was used to conduct triaxial compression tests and seepage
tests on natural and fully saturated rock samples. The experiments aims to study the deformation under various
confining pressure. During the test, both axial and confining pressures were displacement controlled at a rate of
0.001 mm/s. To investigate the influence of in-situ formation pressure on the water softening characteristics of
rock, the confining pressures were set as 0, 4, 6 and 8 MPa, respectively, corresponding to the depth that various
from 0 to 1000 m. A MTS Exceed E45 rock mechanics testing system from China University of Mining and
Technology-Beijing (see Fig. 3b) was used to carry out the Brazilian tests on natural and fully saturated rock
samples. The axial load is also controlled by changing the displacement at a speed of 0.001 mm/s.

3.2 Effect of water softening on compressive characteristics

The compressive properties of natural and saturated sandy mudstones were obtained from uniaxial
compressive and triaxial tests. Tests at each confining pressure were repeated three times. Figure 4 shows the
evolution of circumferential and axial strains with the deviatoric stress under different confining pressure. By
comparing the uniaxial and triaxial compressive stress-strain curves of natural and saturated sandy mudstones, one
can find that the compressive strength of fully saturated rock samples is significantly lower than that of natural
state rock samples. Thereby, the plastic compaction before the peak strength becomes more obvious for fully
saturated rock (A in the figure), whereas the stress failure after the post-peak slows down. In addition, Figure 4
indicates a transition from brittle failure of natural rock to plastic failure of saturated rock (position B). The above
analysis indicate that water injection can significantly increases the plasticity of sandy mudstone. The detailed
softening effect and quantitative analysis of mechanical parameters will be addressed in section 3.4.
3.3 Effect of water softening on tensile characteristics

The Brazilian test was implemented to estimate the tensile strength of the natural and saturated rock samples, and four sets of tests were carried out under each state. Figure 5 shows the force-displacement curves obtained from the Brazilian test. It can be seen from Fig. 5 that the failure strength (force) of the rock sample in the natural state is substantially greater than that of the saturated rock sample. In the natural state, the force and deformation of the sandy mudstone prior to the peak is almost elastic. At the same time, the force after the peak tensile strength drops dramatically and the brittle fracturing of the rock is obvious. On the other hand, the force-displacement
curve and deformation characteristics of Brazilian test for the rock sample in fully saturated state are similar to that of uniaxial and triaxial tests, especially the plastic behavior and fluctuated loading after the peak failure.

![Force-displacement curves of Brazilian test for natural and fully saturated rock samples](image)

**Fig. 5** Force-displacement curves of Brazilian test for natural and fully saturated rock samples

According to the Brazilian test, ultimate tensile strength ($\sigma_t$) of rock can be expressed as:

$$\sigma_t = \frac{1}{n} \sum_{i=1}^{n} \sigma_t = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{2P_i}{\pi R_i} \right)$$

(1)

where $\sigma_t$ is the tensile strength of one particular sample; $P_i$ means the failure load; $R_i$ represents the sample radius; $t_i$ is the thickness of sample; $n$ denotes the number of tests conducted.

Experimental results show that the tensile strengths at the natural state and fully saturated state are 4.03 MPa and 1.38 MPa, respectively. Although the tensile strength drops 66% when the weakly cemented sandy mudstone is saturated by water, the tensile strength keeps 1/10 of its uniaxial compressive strength at each state.

### 3.4 Comparison of mechanical properties between natural and fully saturated rock

Based on the aforementioned experiments, the mechanical properties of samples under natural and fully saturated states are shown below in Table 1.

|          | $\sigma_t$ | $\sigma_t - \sigma_s$ | $E$   | $\nu$ | $\varepsilon_p$ | $C$   | $\psi$ |
|----------|------------|------------------------|-------|-------|-----------------|-------|-------|
| natural  | 35.22      | 0.381                  | 0.20  | 1.22  | 7.32            | 41    |

**Table 1** Mechanical parameters of natural and fully saturated sandy mudstone.
Figure 6 shows the comparison of compressive strength of natural and saturated rock samples under different confining pressures. From Fig. 6, one can find that the compressive strength (deviatoric stress) of sandy mudstone increases with the increasing confining pressure, and the enhancing effects of confining pressure on strength is more obvious for water saturated rocks. For natural sandy mudstone, when the confining pressure increases from 0 MPa to 8 MPa, the compressive strength of the rock increases from 35.22 MPa to 63.24 MPa by an increment of 80%. However, the compressive strength of fully saturated sample increases from 15.09 MPa to 45.17 MPa, which is approximately three times. It is found that water saturation has a significant weakening effect on the compressive strength of Buertai sandy mudstone after comparing the natural rock samples with fully saturated rock samples. When the confining pressure increases from 0 MPa to 4, 6 and 8 MPa, the compressive strength after water saturation decreases by 57%, 45%, 38% and 29%, respectively. Hence, the softening effect of water decreases as the confining pressure increases.
Figure 7 shows the comparison of elastic modulus of natural and fully saturated rock samples under different confining pressures. Table 1 and Fig. 7 both show that the elastic modulus of sandy mudstone increases with the increase of confining pressure, and the increasing proportion for both natural and fully saturated rock are nearly the same. For natural sandy mudstone, when the confining pressure increases from 0 MPa to 8 MPa, the elastic modulus increases from 3.81 GPa to 8.28 GPa, representing a 1.2 times increment. For saturated sandy mudstone, the elastic modulus increases from 2.75 GPa to 6.18 GPa. This is an increase of 1.3 times. Comparing the natural samples with saturated samples, the elastic modulus of saturated samples under different confining pressures is lower than that of the natural state samples under the same confining pressure. The test results also show that the elastic modulus of the rock decreases 25%~30% after being saturated with water.

Figure 8 shows the relationship of Poisson's ratio with confining pressure for natural and saturated rock samples. From the figure, it can be found that the confining pressure has a significant effect on the Poisson's ratio. When the rock sample changes from uniaxial compression to triaxial compression, the Poisson's ratio decreases significantly. When the confining pressure is small, the water saturation induced softening effect on the rock has a significant improvement in the circumferential deformation, resulting in a 16% larger of the Poisson's ratio in the
saturated rock sample than that of the natural state rock sample in uniaxial compression. When the confining pressure is large, the high confining pressure environment has more influence on Poisson’s ratio and the difference in Poisson's ratio between the two states of rock becomes negligible.

Figure 8 The relationship between Poisson's ratio and confining pressure of natural and water-saturated rock samples

Figure 9 compares the strain after post-peak strength of natural and saturated rock samples after uniaxial and triaxial compressive failures under different confining pressures. The test results show that the post-peak strain of sandy mudstone in the natural state and saturated state both decreases with the increasing confining pressure. When the confining pressure is 8 MPa, the post-peak strain decreases 14% and 17% compared with the uniaxial compression situation, respectively. Under different confining pressures, the post-peak strain of the fully saturated sandy mudstone increases with an average increment of 12% comparing with the natural state samples. This indicates that the deformability of rock increases after the saturation of water.
Based on the experimental results, the cohesion and internal friction angle of Buertai sandy mudstone under natural and saturated conditions were also calculated. The cohesions of the rock sample in the natural and fully saturated states are 7.32 MPa and 3.24 MPa, respectively. The cohesion of the rock after saturation decreases by 56%. Thereby, the change in internal friction of sample in the natural and saturated state is relatively small, which reduces from 41° to 36° only.

3.5 Model modification considering softening effect from water injection

Based on the theory of elasticplastic strain, the total strain change of rock can be expressed as:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p$$

(2)

where $d\varepsilon_{ij}^e$ and $d\varepsilon_{ij}^p$ are the increments of the elastic and plastic strain, respectively.

In Eq. (2), $d\varepsilon_{ij}^e$ can be written as (Teng et al. 2018):

$$d\varepsilon_{ij}^e = \frac{1}{2G} \left( \frac{\nu}{E} \delta_{ij} - d\sigma_{ij} \right)$$

(3)

where $\sigma_{ij}$ means the stress tensor, $G=E/2(1+\nu)$ is the shear modulus, $\delta_{ij}$ denotes the Kronecker operator, $\sigma_{ij} = \sigma_1 + \sigma_2 + \sigma_3$ is the total principal stress.

Besides, $d\varepsilon_{ij}^p$ can be expressed as (Wang et al. 2020):
in which $\gamma$ represents the plastic factor, $\varphi$ is the internal friction angle and $g$ is the plastic function.

Considering the water softening effect and the pore pressure effect on effective stress, $d\varepsilon_{ij}^e$ can be modified as:

$$
\begin{align*}
\sigma_{ij}^e &= 2\varepsilon_{ij}^e \cdot dG(\theta) + 2G(\theta) \cdot d\varepsilon_{ij}^e + \delta_{ij} \cdot dM(\theta) \\
&+ M(\theta)\delta_{ij} \cdot d\varepsilon_{ij}^p - \alpha\delta_{ij} \cdot dp \\
M &= 2G(\theta)\nu(\theta)/[1-2\nu(\theta)]
\end{align*}
$$

where, $p$ is pore pressure in the fractures, $\alpha$ means the Biot's coefficient.

Whereas, $d\varepsilon_{ij}^p$ can be modified as:

$$
\begin{align*}
\varepsilon_{ij}^p &= d\gamma(\theta) \cdot \frac{\delta{g}}{\partial(\sigma_{ij}^p - \alpha p)} \\
g &= \sigma_{ij}(\theta) - \frac{1 + \sin \varphi(\theta)}{1 - \sin \varphi(\theta)} \sigma_{ij}(\theta)
\end{align*}
$$

Eq.(3), Eq.(5) and Eq.(6) form the modified constitutive model by considering the softening effect of water saturation on rock.

### 3.6 Discussion on constitutive model of sandy mudstone

Water has significant softening effect on sandy mudstone. However, previous studies on rock deformation and water seepage problems in mine engineering mostly neglected the modification of the constitutive models. The above mentioned modified method for the constitutive model considering the softening effect of water injection into rock mass provides a simplified solution. The constitutive model in Eq.(6) can be validated and simplified by certain tests, and subsequently used in the development of numerical program in rock engineering.

Take the background of the samples in this work from the roof of Buertai mine, Shendong coal mining area as an example, the sandy mudstone is in an elastic compression state in the in-situ stress field. From the test results in Section 3.4, it can be seen that the changes in Poisson's ratio and internal friction angle of the rock before and after...
water softening under a certain confining pressure (depth) are minimal enough to be ignored. The elastic modulus decreases by about 30% under different confining pressures. By substituting these conclusions into Eq.(6), one obtains

\[
d\sigma_{ij}^e = \frac{\nu}{1+\nu} \left( \frac{1}{\nu} \varepsilon_{ij}^e + \frac{1}{1-2\nu} \delta_{ij} \varepsilon_{kk} \right) \cdot dE(\theta) + \frac{E(\theta)}{1+\nu} \cdot dE_{ij}^v
\]

Furthermore, by implementing more experiments to obtain \( E(\theta), \nu \) and \( \alpha \), Eq.(7) can be further simplified. Alternatively, numerical solution can be gathered by using existing numerical software, which will not be described here.

### 4 Couplings among stress-damage-seepage and permeability model

#### 4.1 Experimental design and procedures

For the fully saturated sandy mudstone samples, a full-process permeability test during the triaxial compression was carried out to study the coupled stress-deformation-seepage interactions. The confining pressure was applied to the rock sample at a loading rate of 1 MPa/min to a specified target of 3 MPa, and kept constant. This confining pressure corresponds to a depth of about 400 m. The axial pressure was applied by displacement control and stress servo loading method. The displacement rate was 0.02 mm/min. The water pressure at the inlet of the rock sample was controlled at 1.1 MPa and the outlet was connected to atmosphere. After the seepage was stabilized, the rock sample was tested for axial deformation and flow velocity under triaxial compression. The test was repeated for twice under each axial pressure with a time interval of not less than 1 min. After the test under one axial pressure was completed, the axial pressure was increased by 2-3 MPal. The measurement was performed again until the rock sample was completely failed.

#### 4.2 Analysis on stress-seepage couplings

Figure 10 shows the co-evolution relationship of stress-strain and permeability of sandy mudstone in the complete triaxial compression. It is clear that the permeability process of sandy mudstone under the triaxial
loading can be divided into three stages. The first stage is the seepage shielding stage. At this stage, the permeability of the rock decreases with the increase of the stress level, from the initial value of 0.056 mD to 0.014 mD. The reason is that the effective stress closes the pre-existing fractures in the samples. By comparing the stress-strain curve with the seepage evolution curve, it can be found that the seepage shielding stage corresponds to the pre-peak compaction, elastic and initial plastic damage stages. The second stage is the seepage surge stage. As the rock sample is compressed and failed, the original fractures in the rock sample further develop and join together accompanied by newly formed fractures. The permeability increases significantly from 0.014 mD to 0.27 mD, and this is 3.8 times of its initial permeability. The seepage surge stage corresponds to the late plastic damage stage and failure stage of the rock sample under triaxial compression. The third stage is the seepage recovery stage. The permeability of the rock sample decreases and recovers with post-peak deformation. The fully saturated sandy mudstone has weak cementation from the previous rock hydraulic effects. It can be seen from Fig. 10 that obvious rheological behavior appears after rock failure. It results water filling in fractures, dislocation or further compaction, which ultimately leads to a decrease in permeability. The seepage recovery stage corresponds to the post-peak rheological stage in the triaxial test. The reality is obvious that the permeability of rock in the late stage III could not keep dropping at a high rate, and the permeability will become stable with the increase of deformation after failure. In Fig. 10, the seepage rate of the late stage III gradually decreases. In this test, the post-peak permeability test data is limited and the process is not fully captured.
4.3 A coupled stress-damage-permeability model on sandy mudstone

Assuming the opening width of the fracture is $b$, the mean tortuosity is $\tau$, the crack length per unit area is $L$ and the fracturing area per unit volume is $S$, the permeability (Xue et al. 2015) and porosity for fractured rock in layers can be estimated as:

$$ k = \frac{L}{12 \tau} b^3 $$

$$ \phi = bS $$

By substituting Eq.(9) into Eq.(8), one obtains

$$ k = \frac{L}{12 \tau S} \phi^3 $$

The partial derivative of the permeability to the effective stress in Eq.(10) can be expressed as

$$ \frac{\partial k}{\partial \sigma_e} = \frac{L \phi^2}{4 \tau S^3} \frac{\partial \phi}{\partial \sigma_e} = 3D_f k $$

$$ D_f = \frac{1}{\phi} \frac{\partial \phi}{\partial \sigma_e} $$

where $D_f$ means the effective stress effect on porosity, which is proportional to rock damage, i.e. $D_f = \lambda_f D$.

$\lambda_f$ is the coefficient of fracture development on effective stress, which can be represented by $\lambda_f = -\lambda_k c_f$ in which $\lambda_k$ denotes the coefficient of damage on permeability.

By substituting rock damage and compression coefficients into Eq.(11), one finds that

$$ \frac{\partial k}{\partial \sigma_e} = -3\lambda_k c_f Dk $$

By integrating Eq.(12), one gets

$$ k = k_0 e^{-3\lambda_f D(\sigma_e - \sigma_0)} $$

where 0 means the initial values.

Eq.(13) shows a permeability model for rock mass based on the evolution of stress and damage. It can be seen
that the rock permeability has an inverse exponential relationship with the effective stress. In particular, it should
be noted that the damage of rock can be further defined according to specific observation methods, such as the
using of extensive elastic modulus degradation, i.e. $D = 1 - \frac{E}{E_0}$. Besides, when considering changes of the
conditions of the rock, the basic mechanical properties in the model are no longer constants. For example,
considering the softening effect caused by water injection in weakly cemented sandy mudstone, the permeability
model can be expressed as:

$$\frac{k}{k_0} = e^{-3\lambda_f (\theta_E \sigma_e) \left[1 - E(\theta)E_0\right] (\sigma_e - \sigma_{e0})}$$ (14)

in which $\theta$ means the water content and $\sigma_e$ denotes the effect of pore pressure.

### 4.4 Model validation

The permeability model proposed in this study is to validate by the sandy mudstone data and permeability test
results. Figure 11 shows the verification results of the coupled stress-damage-permeability model with the model
verification parameters in Table 2. It can be seen that the experimental results are in line with the model calculation
result.

![Fig. 11 Verification of permeability model in the complete process of rock compression](image)

**Table 2** Parameters for permeability model validation

| Parameter | $\theta$ | $E_0(\theta)$ | $\sigma_{e0}$ | $k_{min}$ | $\lambda_f$ | $R^2$ |
|-----------|---------|---------------|--------------|-----------|-----------|-------|
| Magnitude | 5.9     | 2.27          | 0            | 0.014     | 0.316     | 0.96  |
5 Conclusion

In this paper, the hydraulic effect and seepage behavior of weakly cemented sandy mudstone in the Buertai coal mine of Shendong mining area were systematically studied. Based on the experimental results, a modified constitutive model considering softening effect of water injection and a stress-damage-driven model for permeability evolution were proposed to incorporate stress-damage-seepage couplings. The following conclusions can be drawn:

(1) Water softening on weakly cemented sandy mudstone is significant. After water saturation, the plasticity of increases, the compressive strength decreases by 29%~57%. Thereby, the smaller the confining pressure, the higher the softening effect on compressive strength. The modulus of elasticity decreases by 25%~30%. Although, the modulus of elasticity increases with the increasing confining pressure, the incremental ratio for natural and saturated rocks under compression was similar. Changes in Poisson's ratio change are relatively weak that can be ignored under both high and low confining pressures. The post-peak dropped strain decreases with the increase of the confining pressure, but it increases 12% after water saturation under any confining pressure. Besides, the cohesion decreases by 56% and the internal friction angle decreases by 12%. The ultimate tensile strength decreases by 66%.

(2) The evolution of rock permeability of weakly cemented sandy mudstone during triaxial compression is corresponding to rock complete compressional deformation that can be divided into seepage shielding, seepage surge and seepage recovery stages. The permeability at each stage has a negative exponential relationship with effective stress.
The research results can effectively enrich the fundamental theory of rock mechanics and provide guidance for the engineering practices of hard roof pressure relief, underground reservoir construction and the prevention of mine water disaster.

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Author’s contributions

TT and JG: Writing original draft & Data processing. XZ: Methodology, Review & Editing. YW: Review & Editing. ZL: Data processing.

Conflict of interest

All the authors of this manuscript have approved the article’s submission for publication, and there are no conflicts of interest to declare. This paper has not been published elsewhere and is not under consideration by another journal.

Data availability

The data appearing in the manuscript is available by contacting the corresponding author after the publication of the manuscript.

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