Investigating mechanical properties of purplish-red siltstones and mudstones

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Abstract. We investigate mechanical properties and energy conversion patterns of special rock types (purplish-red siltstones and mudstones) broadly distributed in the Three Gorges Reservoir (TGR) area, China. The mechanical properties deteriorate under unloading conditions. For loading conditions, the cumulative dissipation energy is slightly lower than elastic strain energy before crack propagation stage, while after crack propagation stage the elastic strain energy converts into cumulative dissipation energy. Similar energy conversion patterns are found for unloading conditions. This work offers a new perspective into the failure mechanism of the two special rock types.

1. Introduction

Rock mass associated with underground engineering is conditioned by triaxial ground stress before excavation [1]. Certainly, the rock mass excavation is usually an unloading process, which significantly alters the original stress state [2]. As the excavation continues, the rock mass mechanical properties are weakened, thereby destabilizing the rock mass itself [3,4]. The rock mass under unloading conditions differ considerably from that under loading conditions in behaviors, such as the constitutive relationships, mechanical evolution patterns and deformation and failure patterns [5].

Laboratory triaxial loading tests and triaxial unloading tests allow to reveal the deformation properties and the energy conversion patterns of rocks. In the past decade, progresses have been made in evaluating the properties of rock mass under loading conditions or under unloading conditions [6-8] and the loading theory is therefore formed for estimating the mechanical parameters [9,10]. This widely used loading theory, however, is not well suited to the unloading conditions [11,12]. Therefore, it is becoming very necessary to understand their mechanical properties under loading and especially unloading conditions.

Recent perspective states that the failure phenomena of rocks are caused by energy-driven instability, which is an irreversible process of energy dissipation experiencing local dissipation, followed by local failure and finally overall destruction (e.g., [13]). Previous researches on rocks under different stress paths from the perspective of energy concentrate on the variation in physical
properties [14,15], yet their differences are rarely revealed from this perspective. The energy dissipation tends to lead to the rock degradation and strength reduction, while sudden overall destruction is partly due to the energy release [1,16]. At present, the researches about influences of the confining pressure on energy input/output remain lacking, which is of great importance for determining strength yielding criteria during a complete deformation and failure process. During the process, the energy conversion is dynamic. There is a mutual balance and conversion between various energies [17]. The effects of loading path on the energy conversion of rocks would be different from that of unloading path. Therefore, understanding the energy conversion patterns during a complete deformation and failure process are of significance [13].

In this study, we conduct triaxial loading tests and unloading tests of purplish-red siltstones and purplish-red mudstones. Mechanical properties are analyzed and the energy conversion patterns are investigated.

2. Preparation of siltstone and mudstone specimens and test/analysis methodologies

2.1. Specimens preparation
The rock samples were collected from a slope located in Dongrangkou Town, Badong County, in the TGR area. The first type of lithology is purplish-red siltstones from Badong Formation Section Two (b2), Middle Triassic. The second type of lithology is purplish-red mudstones from Badong Formation Section Four (b4), Middle Triassic. Triaxial loading tests and triaxial unloading tests of purplish-red siltstones and purplish-red mudstones were conducted in Chinese Academy of Sciences. The relative error in the axial strain measurement was no more than 0.6%, and the relative error in lateral strain measurement was no more than 1.3%.

2.2. Test method
In order to reveal the mechanical properties and the energy conversion patterns of purplish-red siltstones and mudstones under loading and unloading conditions, the initial \( \sigma_3 \) is set to be four levels, that is 2, 4, 8 and 16 MPa.

In the loading tests, \( \sigma_3 \) is unchanged but the axial stress is increased. Moreover, the axial stress-controlled method is employed to guarantee unchanged loading rate. Afterwards, keeping \( \sigma_3 \) stable, the axial stress is loaded until the rock sample is broken.

In the unloading tests, the axial stress is unchanged but \( \sigma_3 \) is decreased. Initially, the axial stress-controlled method is also employed to guarantee unchanged loading rate before the axial stress reaches 80% of peak strength (PS). Then, the control method is transformed into the strain control. Specifically, the axial stress and \( \sigma_3 \) is loaded. Afterwards, keeping the axial stress stable when it reaches 80% of the PS, \( \sigma_3 \) is unloaded until rock sample is destroyed.

2.3. Energy parameters determination method
The formation and coalescence of microcracks that cause rock deformation and failure are energy consuming, the dissipation energy (DE) represents the reduction degree of the initial rock strength. The energy distribution patterns based on the stress-strain relationships are obtained, which is referred in reference [18]. The total absorption energy is simplified as TAE. The elastic strain energy is simplified as ESE. Moreover, the cumulative dissipation energy is simplified as CDE. According to the energy conservation theorem and the first law of thermodynamics, the equations of TAE, ESE and CDE can be obtained by [18].

3. Test/analysis results

3.1. Mechanical properties

3.1.1. Loading conditions. Figure 1 presents the measured curves under loading conditions. With the
increase of $\sigma_3$, the ductility of b2 rocks are more obvious, while the ductility of b4 rocks are not distinct. Moreover, when $\sigma_3=16$ MPa, the brittle characteristic of b4 rocks is more obvious than that under low $\sigma_3$ (2, 4 and 8 MPa). For b2 rocks, the PS in cases of $\sigma_3=16$ MPa is two times larger than that in cases of $\sigma_3=8$ MPa. During the period from 80% of the PS to the PS, the damage of the rock is aggravated and it will soon reach the critical point of the destruction of the rock. After the PS, the stress of b2 rocks decreases rapidly with a multilevel failure characteristic, which embodies in three strength reductions in the $\sigma_3$ of 2 MPa, and two strength reductions in the $\sigma_3$ of 4 MPa and 8 MPa, with the exception of the $\sigma_3$ of 16 MPa.

![Figure 1](image1.png)

**Figure 1.** The curves of red bed rocks for triaxial loading tests. (a) b2 rock. (b) b4 rocks.

Under loading conditions, the mechanical parameters of red bed rocks are shown in Table 1. As $\sigma_3$ increases, the PS and the RS gradually increase. The ratios of the RS to the PS are approximately 0.5, except for b4-2-1 rock. The range of the elastic modulus of b4 rocks is 12-14 GPa, while the Poisson’s ratio is approximately 0.3 under different $\sigma_3$, which are less than those of b2 rocks. The results also illustrate that $c$ of b4 rocks at the PS or at the RS are higher than that of b2 rocks, while $\phi$ at the PS or at the RS are less than that of b2 rocks, indicating that the mechanical parameters of rocks are deteriorated. Furthermore, for b2 rocks, the angle of rupture $\beta$ decreases when $\sigma_3$ increases from 2 MPa to 8 MPa, and then increases with increasing of $\sigma_3$.

| Rock type | PS parameters | RS parameters |
|-----------|---------------|---------------|
|           | $c$ (MPa)    | $\phi$ (°)    | $c$ (MPa)    | $\phi$ (°)    |
| b2        | 10.0          | 57            | 6.0          | 37            |
| b4        | 25.6          | 32            | 10.9         | 22            |

3.1.2. Unloading conditions. The measured curves under unloading conditions is shown in figure 2. With $\sigma_3$ increased, the ductility of b2 rocks are more obvious. b2 rock failure is rapid and abrupt. However, for b4 rocks, the axial strain after the PS is also greater than the axial strain for loading conditions, while the axial strain at the PS is lower than the axial strain for loading conditions. With the increase of $\sigma_3$, the plastic characteristic is slightly less visibility.

It can be seen from figure 2, as $\sigma_3$ increases, the PS and the RS gradually increase. The PS and the RS are lower than those under loading conditions, indicating that the destruction of the rocks is more serious and the bearing capacity is lower than the loading condition. For b2 rocks, $\sigma_3$ after the failure of the rock is very small or even close to 0 at initial $\sigma_3$ of 2 MPa, 4 MPa and 8 MPa, which hints that the final $\sigma_3$ is affected by the unloading rate. Nevertheless, $\sigma_3$ after rock destroys is approximately 5 MPa at initial $\sigma_3$ of 16 MPa. For b4 rocks, the range of the ratio of the RS to the PS is approximately 0.1-0.2, which is obviously lower than the loading condition. Remarkably, $\sigma_3$ is relatively small when the rock sample is destroyed.
Furthermore, it should be done to destroy the rock sample under high temperature conditions.

3.2. Energy evolution

3.2.1. Loading conditions. To investigate the energy evolution at different $\sigma_3$, some related curves of red bed rocks are plotted in figure 3. Due to the similar trend of the energy conversion at the same stress path, the b2-2-1 rock and the b4-2-1 rock are selected as examples (figure 3). The ESE of b2 rock accounts for a large proportion of the TAE before crack propagation stage while after crack propagation stage, the increasing rate of the ESE reduces. Nevertheless, the CDE is lower than the ESE before crack propagation stage while the CDE increases abruptly after crack propagation stage. The variation pattern of the CDE during the post-peak failure stage is consistent with that of the TAE. Moreover, the ESE-strain curves of b2-2-2 and b2-2-3 rocks are characterized by multistep descent, which is almost identical with the stress-strain curves.

![Energy evolution patterns of red bed rocks under loading conditions](image)

**Figure 3.** The energy evolution patterns of red bed rocks under loading conditions. (a) b2 rock. (b) b4 rock.

For b4 rocks, the increasing trend of the ESE before crack propagation stage is basically consistent with that of the TAE, while the difference between the ESE and the TAE is getting bigger and bigger after crack propagation stage. The change is due to the generation the microcracks and the production of plastic deformation. Furthermore, after the PS, the release of most of the ESE instantaneously is used to accelerate the propagation of the microcracks by transforming into the CDE. It is very obvious that the ESE-strain curves have multistep descent characteristic, which is almost identical with the stress-strain curves, except for the b4-2-4 rock. In contrary, the CDE before crack propagation stage is approximately 0, then the CDE gradually increases as the axial strain climbs. After the PS, the increasing trend of the TAE-strain curves and the CDE-strain curves have similar trends with characterizing of multistep rise. Under high $\sigma_3$, much energy is required to destroy the rock, which is owing to the presence of $\sigma_3$ that restrains the formation of microcracks. Therefore, more external work should be done to destroy the rock sample under high $\sigma_3$.

3.2.2. Unloading conditions. Figure 4 plots the related curves of red bed rocks under unloading conditions. For b2 rocks, the increasing trend of the ESE before crack propagation stage is basically consistent with that of the TAE, while the difference between the ESE and the TAE is getting bigger and bigger after crack propagation stage. The change is due to the generation the microcracks and the production of plastic deformation. Furthermore, after the PS, the release of most of the ESE instantaneously is used to accelerate the propagation of the microcracks by transforming into the CDE. It is very obvious that the ESE-strain curves have multistep descent characteristic, which is almost identical with the stress-strain curves, except for the b4-2-4 rock. In contrary, the CDE before crack propagation stage is approximately 0, then the CDE gradually increases as the axial strain climbs. After the PS, the increasing trend of the TAE-strain curves and the CDE-strain curves have similar trends with characterizing of multistep rise. Under high $\sigma_3$, much energy is required to destroy the rock, which is owing to the presence of $\sigma_3$ that restrains the formation of microcracks. Therefore, more external work should be done to destroy the rock sample under high $\sigma_3$. 

![Energy evolution patterns of red bed rocks under unloading conditions](image)

**Figure 4.** The energy evolution patterns of red bed rocks under unloading conditions. (a) b2 rock. (b) b4 rock.
conditions. The energy parameters curves of b2 and b4 rocks are similar under different $\sigma$, hence, the b2-3-1 rock and the b4-3-1 rock are just selected to take as examples in figure 4. Before the stress of b2 rocks reaches the PS, the ESE approximately accounts for 90% of the TAE while the increase rate of the ESE reduces. The ESE is up to the maximum at the PS. Afterwards, a large amount of the ESE begins to release and transform into the CDE, which is used to accelerate the development of microcracks for the rock. The evolution patterns of the energy parameters of b2 rocks are basically identical with loading conditions, except for the small CDE before the PS. After the PS, CDE/TAE is larger than the CDE/TAE under loading conditions, and the CDE raises abruptly.

For b4 rocks, the growth rate of the ESE gradually decreases before the PS. The value of the ESE still increases. At the PS, the ESE that approximately accounts for 90% of the TAE is up to the maximum. Afterwards, a large number of the ESE is released to aggravate the development of the microcracks. Finally, the ESE is very small at the RS, especially in $\sigma$ of 2 MPa and 4 MPa. However, the evolution patterns of the CDE are opposite to that of the ESE. At the PS, the CDE increases sharply. The increase rate of the CDE during the post-peak failure stage is basically stable until the stress reaches the RS. Compared with the results under loading conditions, the evolution patterns of the energy parameters under unloading conditions are almost identical.

3.3. Deterioration of deformation parameters

According to the analysis mentioned above, under unloading conditions, the mechanical properties of b2 and b4 rocks are obviously different with loading conditions. The deformation parameters deteriorate chiefly for the expansion, sliding and instability of cracks inside rock during the reduction of $\sigma$. Finally, the quality of rock mass will deteriorate. The deterioration of deformation parameters of these rocks is studied in this study by taking the unloading quality that represents the degree of unloading as a parametric variable, then the relationship between the deformation parameters and the unloading quality, defined as follows:

$$m = \frac{\sigma_{30} - \sigma_3}{\sigma_{30}} \times 100\%$$  \hspace{1cm} (1)

where $m$ is the unloading quality, $\sigma_{30}$ is the initial confining pressure.

Deformation parameters ($E$ and $\mu$) are calculated using the methods proposed in [19]. The Poisson’s ratio in post-peak failure stage is greater than 0.8, which has no original meaning. This is because the surrounding rebound unloading leads to the formation of the microcracks. In addition, the direction of the propagation of the microcracks is perpendicular to the direction of unloading, which results in the transverse expansion intensely. Therefore, only the region from the starting point of unloading to the PS is considered.

The relationships between the deformation parameters and the unloading quality are presented in figure 5, taking b2 rocks as an example. $E$ and $\mu$ of b2 and b4 rocks deteriorate during the unloading,
and the degree of deterioration of the deformation parameters for b2 rocks is larger than that for b4 rocks. Generally, the deterioration effect of the Poisson’s ratio shows a non-linear characteristic with the increase of the unloading quality, while the deformation modulus tends to linearly change. When the unloading quality is small, the deterioration effect of the deformation parameters is not obvious. When the unloading quality reaches 80%, $E$ and $\mu$ change sharply, in which $E$ decreases while $\mu$ increases. This will lead to the decrease of the rock integrity and the increase of the transverse deformation, which is prone to tensile failure. In addition, under higher $\sigma_3$ (i.e. 8 MPa and 16 MPa), the variation of the deformation parameters at the unloading yield stage is larger than that under lower $\sigma_3$. Therefore, the unloading quality can be used to characterize the deterioration of the deformation parameters under unloading conditions.

Due to the non-linear characteristic of the deterioration of $\mu$, the relationship between $\mu$ and the unloading quality can be fitted by polynomial formula $\mu = g(m) = B_0 + B_1*m + B_2*m^2$. In this formula, $B_0$, $B_1$ and $B_2$ are fitting coefficients, respectively, and the fitting results are great, as shown in table 2. However, the deterioration of $E$ presents linear characteristic, so the linear formula $E = f(m) = k*m + b$ can be used to fit their relationship, in which $k$ and $b$ are fitting coefficients. The fitting coefficient $k$ reflects the deterioration degree of $E$ with the change of the unloading quality, while the fitting coefficient $b$ represents the deformation modulus before unloading. The fitting coefficients $k$ and $b$ are shown in table 3.

![Figure 5. The relationships between the deformation parameters and the unloading quality for b2 rocks. (a) Poisson’s ratio. (b) Deformation modulus.](image)

| Table 2. The fitted parameters between Poisson’s ratio and unloading quantity. |
| --- |
| Coefficient | b2 | b4 |
| $\sigma_3=2$ | $\sigma_3=4$ | $\sigma_3=8$ | $\sigma_3=16$ | $\sigma_3=2$ | $\sigma_3=4$ | $\sigma_3=8$ | $\sigma_3=16$ |
| $B_0$ | 0.30 | 0.10 | 0.13 | 0.14 | 0.24 | 0.26 | 0.195 | 0.198 |
| $B_1$ | -0.001 | 0.002 | -0.002 | 2.18E-4 | 2.97E-6 | 2.04E-4 | -0.001 | -1.37E-4 |
| $B_2$ | 19.5E-5 | -10.07E-5 | 30.07E-5 | 7.07E-6 | 5.44E-6 | 2.94E-6 | 2.24E-5 | 4.76E-6 |
| $R^2$ | 0.89 | 0.87 | 0.82 | 0.88 | 0.99 | 0.99 | 0.85 | 0.99 |

| Table 3. The fitted parameters between deformation modulus and unloading quantity. |
| --- |
| Coefficient | b2 | b4 |
| $\sigma_3=2$ | $\sigma_3=4$ | $\sigma_3=8$ | $\sigma_3=16$ | $\sigma_3=2$ | $\sigma_3=4$ | $\sigma_3=8$ | $\sigma_3=16$ |
| $k$ | -0.003 | -0.013 | -0.022 | -0.021 | -0.005 | -0.006 | -0.008 | -0.014 |
| $b$ | 14.02 | 19.79 | 22.60 | 29.92 | 13.33 | 15.12 | 15.32 | 14.78 |
| $R^2$ | 0.83 | 0.92 | 0.90 | 0.86 | 0.98 | 0.99 | 0.88 | 1.00 |

From the above analysis, it can be seen that the deformation parameters deteriorate during unloading process, characterizing by approximately non-linear behavior for the deformation modulus and linear behavior for $\mu$ with the change of unloading quality. The unloading quality is a quantity to
indicate the unloading degree, and its expression includes the confining pressures before and after unloading. However, volume expansion, brittle failure and parameter degradation are sensitive to the initial confining pressure and the unloading degree. Therefore, it is of practical and theoretical significance to utilize the unloading quality to express the degradation of the deformation parameters during unloading of rocks.

4. Discussion
As mentioned earlier, the energy conversion and mechanical properties of b2 and b4 rocks under unloading condition are essentially different from loading condition. The above results make it possible to estimate the mechanical properties and the energy conversion patterns. For example, the mechanical properties of b2 and b4 rocks in TGR area may be determined by dividing the complete stress-strain curves into several different deformation stages, if the test conditions are similar to those in the paper. The energy conversion of b2 and b4 rocks in TGR area may offer the possibility to expose the failure patterns of reservoir slopes from the energy perspective, and determine whether the deformation in reservoir slopes is still in progress or is failure.

The specific application of the results mentioned above is as follows. The Section 2 and Section 4 of Badong formation in the TGR area are typical slippery strata [20]. The instability of reservoir slopes in the urban area of Badong County is closely related to stratum lithology and slope structure. This study about the energy conversion and mechanical properties of b2 and b4 rocks in the TGR area can be conductive to the deformation and failure patterns of reservoir slopes. Due to the difference of the quantity of energy dissipation and the quantity of deformation of b2 and b4 rocks, it is easy to slide along the contact interface between hard rocks and soft rocks, which results in the development of bedding slip zone within the rock mass in Badong urban area. Before the penetration of the sliding surface, the rocks maintain good structures without obvious collapse and fracture occurred [21,22], and the energy dissipation of the rocks that leads to rock damage is relatively small. The results mentioned above show that a large amount of ESE is stored in the rocks before sliding. However, the ESE are suddenly released when forming a through sliding surface near the contact interface, which result in severe sliding. Therefore, this study is of significance in the deformation and failure patterns and the stability assessment of reservoir slopes.

5. Conclusions
Major conclusions regarding the mechanical properties and energy conversion patterns of purplish-red siltstones and mudstones are as follows:

- For loading tests, b2 and b4 rocks under different $\sigma_3$ destroy and the axial stress decreases abruptly, characterizing multilevel descent after the PS. The occurrence of ESE of b2 rock taking up a large proportion of the TAE before crack propagation stage and the CDE increasing sharply can be a criterion of the rock failure.
- For unloading tests, b2 rock failure is rapid and abrupt. Relative to the loading conditions, the evolution patterns of several parameters about energy are mainly identical. However, the mechanical parameters of b2 and b4 rocks are deteriorated. Thus, the failure of the rock under loading conditions is mainly caused by the loading at the axial direction, while the failure of the rock under unloading conditions is due primarily to the expansion at the circumferential direction.

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