Influence of dynamic disturbance on rock creep from time, space and energy aspects

Zhen Yang\textsuperscript{a}, Wancheng Zhu\textsuperscript{a}, Kai Guan\textsuperscript{a}, Baoxu Yan\textsuperscript{a,b} and Hanwen Jia\textsuperscript{a,c}

\textsuperscript{a}Center for Rock Instability and Seismicity Research, Northeastern University, Shenyang, P.R. China; \textsuperscript{b}Energy School, Xi’an University of Science and Technology, Xi’an, P.R. China; \textsuperscript{c}Deep Mining Laboratory, Shandong Gold Group Co., Ltd, Yantai, P.R. China

ABSTRACT
In order to explore the influence of dynamic disturbance on creep behavior of rock, the creep damage evolution in rock under the dynamic disturbance are reproduced with creep damage model. In this model, the constitutive law of rock under combined creep and dynamic loading condition is implemented based on elastic damage principle and Norton-Bailey equation in COMSOL Multiphysics. The numerical results show that the dynamic disturbance alters the creep behavior of rock in three aspects, i.e., time, space and energy. In temporal aspect, dynamic disturbance not only accelerates the creep damage evolution of rock, but also leads to the tensile damage accounting for the main damage mode. The tensile damage mode mainly occurs during the unloading stage of dynamic disturbance, and the tendency of transition becomes evident under more dynamic disturbances. In spatial aspect, the dynamic disturbance may facilitate the development of rock damage, resulting in unstable rock failure. In energy aspect, the dynamic disturbance causes creeping rock to absorb and release energy in a short time, which can be quantified with the energy dissipation rate. The residual deformation caused by the dynamic disturbance is also exponentially related to the energy dissipation rate.

1. Introduction
Rheological properties and aging characteristics are the inherent mechanical properties of rock materials, and the deformation, damage and instability of rock are essentially results of the creep phenomenon under a constant external force. In addition, rock engineering disaster is often triggered by dynamic disturbance such as blasting, which is responsible for one of the most mechanisms for the mining disasters. In this regard, dynamic disturbance often affects the creep behavior and fracture of rock, and even induces rockburst and other dynamic disasters (Malan 1999; Fu et al. 2008;
Zhu et al. 2010; Sun et al. 2018; Zhu et al. 2019). For example, the creep deformation of freezing vertical shafts is affected by dynamic disturbance (Bai et al. 2021). Sliding rock bursts, collapses, and earthquakes may be caused by dynamic disturbance (Wang et al. 2021). Time-dependent rheological behavior of the pillar or roof may be triggered by dynamic disturbance such as rock blasting (Li et al. 2021). Therefore, it is of great significance to further understand the damage and unstable failure of rock induced by dynamic disturbance in order to clarify the mechanism associated with the dynamic disasters such as rockburst.

Numerical simulation is an effective mean to clarify the mechanism of the rock damage and failure. In terms of analyzing the creep effect (Kuhn and Mitchell 1992; He et al. 2011; Wang et al. 2017; Zhou et al. 2020; Gutiérrez-Ch et al. 2021, 2022) and dynamic response (Reddish et al. 2005; Bi et al. 2017; Aziznejad et al. 2018; Li et al. 2018) of rocks, abundant research work was conducted, and fruitful results have been achieved. In creep effect research, He et al. (2011) based on the maximum tensile stress theory, a creep rupture judgment criterion was established, and the initiation, expansion and gathering of creep cracks were simulated by finite element method. Based on the creep experiment of sandstone, Wang et al. (2017) proposed a time-dependent creep model according to a damage constitutive law, in order to simulate the time-dependent behavior of heterogeneous brittle rocks. Zhou et al. (2020) considered the material heterogeneity and local material degradation of rock, and proposed a 3D numerical model to describe time-independent deformation and fracturing of brittle rocks. The essential characteristics of rock creep through the rate process theory (RPT)—i.e., a creep rate that decreased rapidly with time (Gutiérrez-Ch et al. 2021, 2022). In dynamic response research, Aziznejad et al. (2018) used the distinct element code (PFC2D) to generate the bonded particle model (BPM) to simulate both the static and dynamic properties of the intact rock. Bi et al. (2017) proposed a general particle dynamics (GPD) code to simulate crack initiation, propagation, and coalescence of rock-like materials under impact loading. Li et al. (2018) simulated the failure process of a typical hard rock (Carrara marble) under static and dynamic splitting ring tests by using an approach combining the finite element method (FEM) and the discrete element method (DEM), named ELFEN. Reddish et al. (2005) used FLAC2D code to reproduce the process of drop weight impacting cylindrical granite specimens. However, the damage evolution mechanism of creeping rock under the influence of the dynamic disturbance has not been clearly clarified.

As we know that the rock failure is a progressive process, starting from the discrete damage statically distributed in the rock, to the accumulation of several damage zones, until the unstable failure because of coalescence of damage zones to form the macroscopic failure zones. As for the rock specimen under simple loading condition such as uniaxial compression, this whole process can be observed in the laboratory and be simulated with simulators such as COMSOL Multiphysics (Wang et al. 2017; Zhou et al. 2020) and RFPA (Zhu and Tang 2004; Zhu et al. 2007) by using damage mechanics principle.

Therefore, based on the numerical simulation of damage mechanics principle, the rock creep process under the influence of the dynamic disturbance is examined in
this paper. The characteristics of deformation, damage and crack development of creeping rock caused by dynamic disturbance in time, space and energy are emphatically analyzed, and rock creep damage mechanism that is triggered by the dynamic disturbance is also revealed.

2. Governing equations and numerical model

2.1. Governing equations

2.1.1. Damage constitutive equation

The heterogeneity of rock leads to its discrete damage under a variety of loading conditions (Zhu and Tang 2004). In the numerical simulation, the heterogeneity of rock is expressed by the element whose mechanical properties obey Weibull statistic distribution (Zhu et al. 2016; Liu et al. 2018; Xu et al. 2018; Zhou et al. 2020).

Damage to rock is closely related to its stress state. When the stress state of rock meets the maximum tensile stress criterion or the Mohr-Coulomb criterion, rock damage begins to occur (Zhu and Tang 2004). Under any stress condition, the maximum tensile stress criterion is preferred. Damage variables can be expressed as (Zhu et al. 2013):

\[
D = \begin{cases} 
1 - \frac{\varepsilon_{t0}}{\varepsilon_t} & (F_1 = 0 \text{ and } dF_1 > 0) \\
0 & (F_1 < 0 \text{ and } F_2 < 0) \\
1 - \frac{\varepsilon_{c0}}{\varepsilon_c} & (F_2 = 0 \text{ and } dF_2 > 0)
\end{cases}
\]

(1)

Where \(\varepsilon_{t0}\) is the maximum tensile principal strain; \(\varepsilon_{c0}\) the maximum compressive principal strain; \(\varepsilon_1\) is the maximum principal strain; \(\varepsilon_3\) is the minimum principal strain; \(n\) is a constitutive coefficient, set to 2.0. The damage variable is calculated by Eq. (1), and its value is between \(-1\) and \(1\). Shear damage is denoted with positive digit, while tensile damage is denoted with negative digit.

2.1.2. Creep constitutive equation

In order to analyze the long-term stability of rock materials, The Bailey-Norton creep law was introduced to establish the mathematical models of creep. When rock is in creep stress state, its strain consists of two parts: elastic strain and creep strain (Kraus and Saunders 1982). Then the total strain rate of rock under creep stress is finally expressed as (Wang et al. 2017; Xu et al. 2018):

\[
\dot{e}_{ij} = \frac{1 + \nu}{E} \sigma_{ij} - \frac{\nu}{E} \sigma_{kk} \delta_{ij} + \frac{3}{2} S_{ij} A_n \sigma_c n_{ij}^{m-1} n_i n_j^{m-1}
\]

(2)

The damage constitutive equation and creep constitutive equation are implemented into the COMSOL Multiphysics software (a commercial code), and the damage evolution and the axial strain time-historical variation in the process of rock creep under dynamic disturbance are calculated. This model and its implementation had been validated against experimental results in previous publications (Zhu et al. 2016; Wang
et al. 2017; Liu et al. 2018; Zhou et al. 2020). The emphasis of this study lays on the application of this model into rock damage and failure under creep-impact loading.

2.2. Numerical model

In order to verify the reliability of the damage constitutive equation, our numerical model was used to simulate the creep process of rock according to Zhu et al. (2019). In the experiment of Zhu et al. (2019), the diameter and height of the sandstone specimen are both 50 mm. The creep stress selected in this experiment was 19.86 MPa, which corresponds to 60% of the uniaxial compressive strength of sandstone specimen. According to the in-situ blasting practice, the interval of blasting is generally 12 hours, which is the same as the dynamic disturbance interval in this paper. The energy of the sandstone specimen subjected to dynamic disturbance is 14.7 J, which is applied with a 5 kg drop hammer falling freely from a height of 30 cm. The loading path of the creep-impact test of Zhu et al. (2019) are shown in Figure 1.

The laboratory test model was simplified as a plane stress problem, the numerical model of sandstone specimen and steel plate is shown in Figure 2. In the creep stage, roller constraint is applied to the bottom of the model and constant stress ($p_s$) is applied to the top. When the model experiences a dynamic disturbance, coupled static-dynamic stress ($p$) is applied to the top of the model.

The mechanical properties of sandstone specimen are assumed to be heterogeneous and satisfy the Weibull statistic distribution. From the properties of the Weibull distribution, a larger value of homogeneity index $m$ implies a more heterogeneous material and vice versa. For higher values of the homogeneity index $m$, the strengths of more elements are concentrated closer to average (Zhu and Tang 2004). The selection of properties used in the model is generally based on the principle that the numerical specimen matches some basic mechanical properties such as elastic modulus, uniaxial compressive strength of real rock. In order to simplify the analysis, other constitutive parameters such as internal cohesive angle, Poisson’s ratio are fixed.

![Figure 1. Loading path of creep-impact experiment.](image)
throughout all the calculations. $A$, $m_c$ and $n_c$ are experimentally determined parameters. The mechanical parameters of sandstone specimen are listed in Table 1.

3. Model verification

3.1. Model verification of mechanical parameter assignment

In order to verify the reliability of mechanical parameter assignment in numerical simulation, rock failure process under uniaxial compression was also numerically simulated to compare with the experimental results by Zhu et al. (2019) as shown in Figure 3. It is noted that Figure 3 does not show the compaction stage in the rock failure process under uniaxial compression, which is attributed to that the elastic damage constitutive is used in the numerical simulation. These problems will be solved in future studies.

3.2. Model verification for creeping rock under dynamic disturbance

The results of creeping rock mechanical response under the influence of dynamic disturbance obtained by laboratory experiment and numerical simulation are shown in Figure 4. The variation trend of rock axial strain obtained by numerical simulation present is consistent with the laboratory experimental results. Although the deformation of creeping rock in compaction stage is neglected due to elastic damage constitutive, the numerical simulation results reflect the deformation behavior of creeping rock caused by dynamic disturbance. The rate of three creeps before the accelerating creep stage is counted in Table 2. The experimental and numerical simulation data in Table 2 are similar, and the error between the numerical simulation and the experimental results is within 5%. Both sets of data show a monotone increasing trend, which verifies the experimental phenomenon that the rock creep rate is affected by dynamic disturbance, specifically, the creeping rock accelerated after being dynamically disturbed.

In particular, compared with laboratory experiments, the numerical simulation reproduces the deformation process of rock under both the creep stress and dynamic...
disturbance. At the same time, the numerical simulation also shows strain variation, stress migration, damage evolution and crack coalescence inside the rock in time and space dimensions.

Compared with the laboratory test, the numerical simulation obtains the surge and recovery of rock axial strain caused by dynamic disturbance. This process is easily ignored because the strain gauge cannot measure static and dynamic at the same time, which can be made up via the adopted numerical simulation. It should be noted that the numerical results of instantaneous strain caused by creep stress and the residual strain caused by dynamic disturbance are smaller than the laboratory experimental results, which may be attributed to the adopted elastic damage constitutive law of rock. In Figure 4, the compaction strain of sandstone specimen during the experiment is 0.162%. The instantaneous elastic strain obtained by numerical simulation is 0.149% (Figure 4a). The sum of these two strains (i.e., 0.311%) should be considered as the numerical result if the compaction strain is taken into account in the numerical simulation. In contrast, the total experimental strain of sandstone specimen is 0.306% once the creep stress applied initially, as shown in Figure 4a, thus error of strain is 1.63% when it is compared to the strain 0.311%. Considering the discreteness of rock specimens, if the compaction of rock is taken into account the strain error of 1.63% is acceptable.

Table 1. Material properties of the sandstone specimen used for numerical simulation.

| Parameter                        | Unit  | Mesoscopic value | Homogeneity (m) |
|----------------------------------|-------|------------------|-----------------|
| Elasticity modulus (E)           | GPa   | 13.99            | 3               |
| Poisson’s ratio (ν)              |       | 0.29             | -               |
| Uniaxial compressive strength    | MPa   | 88.65            | 3               |
| Internal friction angle          |       | 30               | -               |
| Creep rate coefficient in power law (A) |       | 7.8×10\(^{-11}\) | -               |
| Creep constant (m\(_c\))        |       | 0.37             | -               |
| Creep rate exponent in power law (n\(_c\)) |       | 1.7              | -               |

Figure 3. Stress-strain curve during the rock failure process under uniaxial compression: numerical simulation and experiment.
Figure 5 shows the failure mode of creeping rock under dynamic disturbance. As shown in Figure 5, the rock failure mode reproduced by numerical simulation is similar to that from experimental observation.

Figure 4. Variation process of creeping rock under dynamic disturbance: (a) The time-history variation of axial strain (numerical and experimental results) and (b) Stress migration, damage evolution and crack coalescence in rock (numerical results).
4. Rock creep behavior under dynamic disturbance

The numerical simulation on rock creep failure under dynamic disturbance is carried out in this section, and the mechanical response of creeping rock triggered by dynamic disturbance are examined in depth.

4.1. Temporal response

4.1.1. Deformation characteristics

Figure 6a shows the time-history of axial strain of the creeping rock obtained by numerical simulation. By contrast, Figure 6b presents the numerical result of typical creeping rock without considering dynamic disturbance. It can be clearly seen that the influence of dynamic disturbance on the creeping rock deformation can be reflected in following four aspects:

1. Dynamic disturbance shortens the time-to-failure of rock. Under the creep stress of 19.86 MPa, the time-to-failure of typical creeping rock is totally 817 hours, while the time-to-failure of rock which influenced by three dynamic disturbances was only 39 hours, that is, after the third dynamic disturbance, the rock becomes unstable 3 hours later. Therefore, dynamic disturbance greatly shortens the time-to-failure of creeping rock.

2. Dynamic disturbance accelerates deformation of creeping rock and improves the sensitivity of the rock to creep stress. As shown in Figure 6a, the axial strain rate of four creep processes before and after the three dynamic disturbances are $1.243 \times 10^{-7}$, $1.449 \times 10^{-7}$, $2.262 \times 10^{-7}$, and $4.039 \times 10^{-6}$ 1/s, respectively, and it presents successively upward trend, which indicates that the dynamic disturbance accelerates deformation of creeping rock and the sensitivity to the creep stress.

3. Dynamic disturbance causes residual deformation in the creeping rock, which increases successively with the times of dynamic disturbances. As shown in Figure 6a, the dynamic disturbance leads to the rapid surge and rebound of the axial strain of the creeping rock, and when the dynamic disturbance is over, the axial strain of the creeping rock does not completely recover, leaving a certain degree of residual deformation. The residual deformation induced by the three dynamic disturbances was 0.0013%, 0.0204% and 0.1771%, respectively, indicating that the residual deformation of creeping rock caused by the dynamic disturbances increases successively.

4. Dynamic disturbance improves the deformation capacity and limit strain of the creeping rock. As shown in Figure 6, the limit strain of creeping rock under the
influence of dynamic disturbance is as high as 0.418%, while the limit strain of typical creeping rock is only 0.301%, indicating that dynamic disturbance improves the deformation of creeping rock. The limit strain is considered to be the strain of rock specimen when accelerating creep occurs. The numerical results show that the rock specimen is considered to be unstable when obvious cracks appear in the specimen, and the strain value at this time is the limit strain of rock.

Among the above four aspects of creeping rock deformation behavior triggered by dynamic disturbance, the first three times are consistent with the experimental phenomena of Zhu et al. (2019). This also indicates that the established numerical model can describe the deformation process of creeping rock behavior triggered by dynamic disturbance.

4.1.2. Damage evolution
In the numerical simulation, the number of damage events per unit time in the creeping process of rock under dynamic disturbance were counted, as shown in Figure 7. The count of damage events are used to represent the damage of creeping rock.

Figure 5. Failure mode of creeping rock under the influence of dynamic disturbance: (a) Experiment observation (Zhu et al. 2019) and (b) Numerical results.
rocks under the influence of dynamic disturbances (Zhu and Tang 2004). It is worth noting that the numerical simulation code has the advantage of determining the pattern of damage, that is, it can determine whether the damage inside the rock specimen is tensile damage or shear damage. The evolution of the two patterns of damage is shown in Figure 7.
It can be seen that the damage counts in the first creep process of the rock are mainly shear damage. With the successive application of dynamic disturbance, damage counts inside the creeping rock gradually change to tensile damage, and the tensile damage gradually dominates the rock damage evolution and failure process. Therefore, it can be concluded that the dynamic disturbance raises the sensitivity of tensile damage to external stress, which leads to the dominance of tensile damage on rock damage evolution.

In order to reveal the variation of tensile damage sensitivity of creeping rock to external stress during dynamic disturbance, the variations of the tensile damage counts and shear damage counts during the three dynamic disturbances are plotted in Figure 8. From Figure 8, the evolution of tensile damage and shear damage are embodied in the following two aspects:

1. The creep damage response of rock under the influence of dynamic disturbance shows obvious time-delay characteristics. When the stress wave is applied to the creeping rock specimen, the damage inside the rock does not respond immediately, but shows an obvious time-delay characteristic, which is also manifested by the fact that the peak value of damage events lags behind the peak value of the stress wave. This phenomenon suggests that creeping rock is more sensitive to the unloading stress wave. The acoustic emission characteristics of high-stress rocks under lateral disturbance carried out experimentally by Zhou et al. (2014) also showed similar phenomenon. In addition, the time-delay may also be attributed to the excessive dynamic disturbance velocity. When the stress wave reaches the peak value, the internal cracks inside the rock specimen cannot develop in the first time, which reflects the inertial effect of the material under dynamic disturbance (Zhang and Zhao 2014). The more times the dynamic disturbances, the more obvious the inertia effect and the time-delay characteristic of rock damage relative to stress wave.

Figure 7. The time-history of the tensile damage counts and the shear damage counts during the four creep processes.
2. In the creep process of rock under dynamic disturbance, the initiation of shear damage presents a downward trend, while the initiation of tensile damage increases and becomes dominant gradually. Moreover, the increase in the amount and proportion of tensile damage occurs mainly in the unloading stage of the stress wave. It also shows that the damage mode of creeping rock under dynamic disturbance is mainly affected by unloading disturbance. By comparing the changes of the two damage modes during the three dynamic disturbances, it is found that the sensitivity of tensile damage to unloading disturbance increases gradually with the successive application of dynamic disturbances.

To sum up, dynamic disturbance not only promotes the tensile damage of rock meso-element, but also accelerates the damage evolution of creeping rock. Moreover,
the tensile damage mode mainly occurs in the unloading stage of stress wave, indicating that tensile damage is more sensitive to unloading disturbance, and its sensitivity to unloading wave can be improved when the time of dynamic disturbance increases.

**Figure 9.** Failure mode of creeping rock with/without dynamic disturbance: (a) Two main cracks and four secondary cracks inside the creeping rock under dynamic disturbance and (b) One main crack and two secondary cracks inside the typical creeping rock.
Figure 10. Variation process of stress, damage and elastic modulus inside the rock during the three dynamic disturbances: (a) During the first dynamic disturbance, (b) During the second dynamic disturbance and (c) During the third dynamic disturbance.
Figure 11. Stress-strain curve and energy distribution of creeping rock under dynamic disturbance: (a) During the first dynamic disturbance, (b) During the second dynamic disturbance and (c) During the third dynamic disturbance.
4.2. Spatial response

The failure mode of creeping rock under dynamic disturbance is obviously different from that of typical creeping rock, which is shown in Figure 9. It can be seen that, the creeping rock under dynamic disturbance is more fractured than the one without dynamic disturbance. The above phenomenon indicates that when the creeping rock under the influence of dynamic disturbance, a large number of discrete cracks and more fragments will appear inside the rock. However, when damage initiates in a typical creeping rock, the number of internal cracks is relatively small, the spatial distribution of cracks is relatively concentrated, and fewer chunks are generated when the creeping rock finally is broken.

Accounting that the strain rate of the rock under dynamic disturbance is high, the rock absorbs a lot of energy in a short time, and the energy for cutting the rock specimen also increases accordingly (Hu and Li 2006). As a result, the amount of crack increases, and more fragments are generated in the creeping rock under dynamic disturbance, which can be clarified by rock specific energy absorbency (Kim et al. 2018). With the increase of strain rate, the specific energy absorption rate and the cracks in the rock coalescence increases gradually, which leads to the change from tensile splitting failure mode to brittle failure mode (Li et al. 2019). In addition, according to Griffith criterion, the surface area of the rock broken is proportional to the strain rate, indicating that a higher strain rate leads to a higher energy absorbed by the rock, and a higher number of activated microcracks induces a more coalescence failure of rock.

In order to reveal the mechanism of the dynamic disturbance changing the failure mode of creeping rock, the changes of stress, damage and elastic modulus inside the rock during the three dynamic disturbances are shown in Figure 10. Stress migration and damage evolution in rock specimen caused by dynamic disturbance are simulated, which is embodied in the following three aspects:

1. The damage evolution of creeping rock under dynamic disturbance is closely accompanied with the stress migration inside the rock. The change of the first principal stress (tensile stress) dominates the damage evolution and crack coalescence under dynamic disturbance.

2. Dynamic disturbance leads to the formation of more micro-cracks. With more dynamic disturbances and continuous creep stress, the micro-cracks gradually initiate, propagate and connect with each other, and eventually lead to a large number of fragments. This phenomenon can be attributed to the dynamic disturbance causing the stress wave to reflect back and forth inside the rock, which will continuously produce a large number of shear wave and tensile wave, and the location where the maximum allowable effective stress of the rock first is reached will be damaged and then crack can be coalesced.

3. Under dynamic disturbance, the main crack of creeping rock gradually deflects to the direction of the first principal stress, which is in agreement with Chen et al. (2018) that the crack under dynamic disturbance was more likely to pass through the grains quickly and grow along the direction of the first principal stress.
To sum up, the development, propagation and coalescence behavior of cracks inside the creeping rock are facilitated by dynamic disturbance. In this respect, dynamic disturbance not only changes the crack coalescence direction, but also makes the rock more fragmented. Many cracks are generated and gradually deflected towards the direction of the first principal stress, eventually forming a large number of fragments.

4.3. Energy release and residual deformation

It is widely accepted that the energy release is one of the direct factors to induce rock instability (Chen and Wang 2013; Fu et al. 2017; Tarasov and Stacey 2017; Wang et al. 2017; Wang and Kaunda 2019; Gao et al. 2020). Therefore, from the perspective of the energy absorption and release, this section explores the mechanism of creeping rock mechanical behavior change induced by dynamic disturbance. It should be noted that the study of the energy absorption and release of rock specimen under creep-impact loading is based on the basic assumption that there is no heat exchange between rock specimen and the outside world.

The stress-strain curve of creeping rock under dynamic disturbance is shown in Figure 11. Curve $O-A-B-C$ is the stress-strain curve of the creeping rock subjected to dynamic disturbance, and curve $C-D$ is the one that the rock specimen initiates to recover deformation until keeping stability under creep stress after the dynamic disturbance. The front of the stress pulse arrives at the top end of the specimen at point $O$, while the peak stress of the stress wave arrives at point $A$, then the limit strain of the rock is attained at point $B$, and the end of the stress pulse arrives at point $C$. Correspondingly, $O-A$ is the loading stage of stress pulse, which can be characterized by the continuous applying of external stress on rock specimen and the continuous increase of axial deformation. $A-B$ is the first unloading stage, during which the external stress begins to decreases, while the axial deformation continues to increase. $B-C$ is the second unloading stage, which represents the unloading of external stress and the rebound of axial deformation. After the dynamic disturbance, the deformation of rock specimen still continues to rebound under the creep stress (see the $C-D$ stage). $D-O$ is the residual deformation after dynamic disturbance.

The energy released/absorbed by stressed rock can be calculated by the integral of the stress-strain curve. The integral results for the loading stage ($OA$ section) and the

|                     | Energy absorbed during the loading stage of stress pulse $E_{x1}/J$ | Energy absorbed during the first unloading stage $E_{x2}/J$ | Elastic strain energy released during the second unloading stage $E_e/J$ | Dissipation energy $E_d/J$ | Residual strain (%) | Energy consumption ratio $k_u$ |
|---------------------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|--------------------------|---------------------|-------------------------------|
| 1st dynamic disturbance | 2.947                                                         | 1.067                                                         | 2.483                                                         | 1.531                    | 0.128               | 0.617                         |
| 2nd dynamic disturbance | 3.280                                                         | 0.750                                                         | 2.138                                                         | 1.890                    | 2.04                | 0.884                         |
| 3rd dynamic disturbance | 3.846                                                         | 2.104                                                         | 0.158                                                         | 6.108                    | 17.11               | 38.670                        |
first unloading stage (AB section) are the total work induced by dynamic disturbance on rock specimen, which is represented by the total energy $E_x$ absorbed during dynamic disturbance. For the second unloading stage (BC section) and the stage where the axial strain of the rock continues to rebound after the dynamic disturbance (CD section), their integral values are the elastic strain energy $E_e$ released by the rock specimen (Jin et al. 2013). According to the law of conservation of energy, the dissipated energy $E_d$ is obtained by subtracting the elastic strain energy $E_e$ released by the rock from the total work $E_x$ (Xie et al. 2011; Chen and Wang 2013; Zhang et al. 2017; Wang et al. 2020), which is the area of the hysteretic loop.

The total work induced by the dynamic disturbance on the rock specimen consists of the work $E_{x1}$ at the loading stage (OA section) (represented by the purple area in Figure 11) and the work $E_{x2}$ at the first unloading stage (AB section) (represented by the blue area in Figure 11), i.e.,

$$E_x = E_{x1} + E_{x2} \quad (3)$$

According to the law of conservation of energy, all the energy absorbed by rock specimen will be converted into elastic strain energy $E_e$ (represented by the shaded area of grid in Figure 11) and dissipated energy $E_d$ (represented by the shaded area of diagonal line in Figure 11). Dissipative energy is used to compaction deformation, cracks propagation inside rock and macroscopic fracture surfaces formation (Jin et al. 2013). Therefore, the total energy absorbed by the rock can also be expressed as:

$$E_x = E_e + E_d \quad (4)$$

In addition, the process from the stable state to the unstable state of the rock specimen is the one related to abrupt energy transformation within the rock specimen (Chen et al. 2020; Gong et al. 2021). Therefore, the energy consumption ratio $k_u$ (the ratio of the energy $E_d$ consumed by rock damage evolution and residual deformation to the elastic strain energy $E_e$) can be used to characterize the internal damage accumulation of rock during the dynamic disturbance, that is

$$k_u = E_d/E_e \quad (5)$$
The energy consumption ratio $k_u$ can reflect the relatively stable state of the rock specimen under loading (Li and Cai 2021). When $k_u < 1$, it can be considered that the elastic energy accumulated inside the loaded rock specimen is much greater than the dissipated energy, and the rock specimen is in a relatively stable state. When $k_u = 1$, the rock specimen can be considered to be in a critically stable state. When $k_u > 1$, the rock can be considered to be in an unstable state.

According to Figure 11, the energy absorption and dissipation of the creeping rock are calculated, as shown in Table 3. The energy consumption ratios during the three dynamic disturbances are calculated as 0.617, 0.884 and 38.670, respectively. It can be seen that the rock subjected to the first two dynamic disturbances is still in a stable state, while under the third dynamic disturbance the rock specimen is in an unstable state, with a great risk of rock instability. The numerical simulation results show that the rock specimen after third dynamic disturbances becomes unstable quickly under the creep stress, which also verifies the validity by judging the rock stability under the creep-impact loading based on the energy consumption ratio.

As shown in Figure 12, the fitting curve shows that the residual strain of the creeping rock induced by dynamic disturbance is positively correlated with energy consumption ratio in an exponential manner. Therefore, it can be concluded that the residual strain caused by dynamic disturbance is closely related to its energy distribution characteristics (energy consumption ratio $k_u$).

5. Conclusion

Stress migration and damage evolution inside creeping rock under dynamic disturbance are numerically simulated. The main conclusions are drawn as following:

1. Dynamic disturbance not only accelerates the creep damage evolution of rock, but also leads to the tensile damage becoming the main damage mode, which induces the rapid rock instability. The tensile damage mode mainly occurs in the unloading stage of dynamic disturbance, and the tendency of transition becomes evident in the case of more times of dynamic disturbances.
2. Dynamic disturbance facilitates the development and propagation of rock damage. With more dynamic disturbances and continuous creep stress, the micro-cracks gradually initiate, propagate and connect with each other, and eventually lead to a large number of fragments. Under dynamic disturbance, more cracks are generated and gradually deflected towards the direction of the first principal stress (tensile stress), and a large number of fragments are formed.
3. Dynamic disturbance induces the creeping rock to absorb and release energy in a short time, which can be quantified with the energy dissipation rate. Based on the energy dissipation rate, the influence of dynamic disturbance on the stability of creeping rock can be judged properly. Moreover, the residual deformation caused by the dynamic disturbance is also closely related to the energy dissipation rate.
Symbols

- $f_{q0}$, $f_{c0}$: Tensile strength and uniaxial compressive strength of the rock element
- $e_{q0}$, $e_{c0}$: Maximum tensile principal strain and maximum compressive principal strain
- $e_1$, $e_2$: Maximum principal strain and minimum principal strain
- $n$: Constitutive coefficient
- $D$: Damage variable
- $\sigma_{kk}$: The first invariant of the stress tensor
- $\sigma_{ij}$: Stress tensor
- $\delta_{ij}$: Kronecker function
- $\nu$: Poisson’s ratio
- $E$: Elastic modulus
- $A$, $n_c$, $m_c$: Creep rate coefficient, hardening exponent, and stress exponent
- $\dot{\varepsilon}_{ij}$: Creep strain rate
- $S_{ij}$: The deviatoric part of $\sigma_{ij}$
- $\dot{\varepsilon}_t$: Effective stress
- $\dot{\varepsilon}_{ij}^t$: Total strain rate
- $E_x$: Total energy
- $E_s$, $E_d$: Elastic strain energy and dissipated energy
- $E_{x1}$, $E_{x2}$: The work at the loading stage and the work at the first unloading stage
- $k_u$: Energy consumption ratio

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China (Grant Nos. U1906208, 51874069 and 52004053); the Fundamental Research Funds for the Central Universities of China (Grant Nos. N180106003, N2001034, N2101015).

Data availability statement

Participants of this study did not agree for the data to be shared publicly, so supporting data is not available.

References

Aziznejad S, Esmaieli K, Hadjigeorgiou J, Labrie D. 2018. Responses of jointed rock masses subjected to impact loading. J Rock Mech Geotech Eng. 10(4):624–634.
Bai Y, Shan R, Tong X, Han T, Dou H. 2021. Study on the effect of dynamic disturbance on creep behavior of frozen fractured red sandstone. Mech Time-Depend Mater.
Bi J, Zhou XP, Xu XM. 2017. Numerical simulation of failure process of rock-like materials subjected to impact loads. Int J Geomech. 17(3):04016073.
Chen XG, Wang Y. 2013. Energy dissipation and release during rock burst. Disaster Adv. 6(9):48–54.
Chen YL, Wu HS, Pu H, Zhang K, Ju F, Wu Y, Liu JF. 2020. Investigations of damage characteristics in rock material subjected to the joint effect of cyclic loading and impact. Energies. 13(9):2154.
Chen CF, Xu T, Li SH. 2018. Microcrack evolution and associated deformation and strength properties of sandstone samples subjected to various strain rates. Minerals. 8(6):231.

Fu J, Song W, Tan Y. 2017. Criterion of local energy release rate of gob instability in deep mines considering unloading stress path. Int J Min Sci Technol. 27(6):1011–1017.

Fu ZL, Zheng YR, Liu YX. 2008. Rock bending creep and disturbance effects. J Cent South Univ Technol. 15(51):438–442.

Gao L, Gao F, Zhang ZZ, Xing Y. 2020. Research on the energy evolution characteristics and the failure intensity of rocks. Int J Min Sci Technol. 30(5):705–713.

Gong FQ, Wang YL, Wang ZG, Pan JF, Luo S. 2021. A new criterion of coal burst proneness based on the residual elastic energy index. Int J Min Sci Technol. 31(4):553–563.

Gutiérrez-Ch JG, Senent S, Estebanez E, Jimenez R. 2021. Discrete element modelling of rock creep behaviour using rate process theory. Can Geotech J. 58(8):1231–1246.

Gutiérrez-Ch JG, Senent S, Zeng P, Jimenez R. 2022. DEM simulation of rock creep in tunnels using rate process theory. Comput Geotech. 142:104559.

He F, Wang LG, Yao Z, Zhang L, Zhao G. 2011. The creep rupture numerical simulation of coal (rock) layered slope. Adv Mater Res. 250–253:271–277.

Hu LQ, Li XB. 2006. Damage and fragmentation of rock under experiencing impact load. J Cent South Univ Technol. 13(4):432–437.

Jin JF, Li XB, Chang JR, Tao W, Qiu C. 2013. Stress-strain curve and stress wave characteristics of rock subjected to cyclic impact loadings. Explos Shock Waves. 33(6):613–619.

Kim E, Garcia A, Changani H. 2018. Fragmentation and energy absorption characteristics of Red, Berea and Buff sandstones based on different loading rates and water contents. Comput Geotech. 142(151):151–159.

Kraus H, Saunders H. 1982. Creep analysis. J Mech Des. 104(3):530–530.

Kuhn MR, Mitchell JK. 1992. Modelling of soil creep with the discrete element method. Eng Comput. 9(2):277–287.

Li P, Cai MF. 2021. Energy evolution mechanism and failure criteria of jointed surrounding rock under uniaxial compression. J Cent South Univ. 28(6):1857–1874.

Li XB, Feng F, Li DY. 2018. Numerical simulation of rock failure under static and dynamic loading by splitting test of circular ring. Eng Fract Mech. 188:184–201.

Li ZJ, Hao JW, Gan DQ, Liu ZY. 2019. An experimental study on the failure characteristics of magnetite ore based on dynamic load. J Vib Shock. 38(12):231–238 and 245.

Liu LY, Zhu WC, Wei CH, Elsworth D, Wang JH. 2018. Microcrack-based geomechanical modeling of rock-gas interaction during supercritical CO2 fracturing. J Pet Sci Eng. 164:91–102.

Li S, Zhu W, Niu L, Guan K, Xu T. 2021. Experimental study on creep of double-rock samples disturbed by dynamic impact. Int J Rock Mech Min Sci. 146:104895.

Malan DF. 1999. Time-dependent behaviour of deep level tabular excavations in hard rock. Rock Mech Rock Eng. 32(2):123–155.

Reddish D, Stace LR, Vanichkobchinda P, Whittles DN. 2005. Numerical simulation of the dynamic impact breakage testing of rock. Int J Rock Mech Min Sci. 42(2):167–176.

Sun Q, Li B, Tian S, Cai C, Xia YJ. 2018. Creep properties of geopolymer cemented coal gangue-fly ash backfill under dynamic disturbance. Constr Build Mater. 191(10):644–654.

Tarasov BG, Stacey TR. 2017. Features of the energy balance and fragmentation mechanisms at spontaneous failure of class I and class II rocks. Rock Mech Rock Eng. 50(10):2563–2584.

Wang Z, Gu L, Zhang Q, Jang B-A. 2021. Influence of initial stress and deformation states on the shear creep behavior of rock discontinuities with different joint roughness coefficients. Rock Mech Rock Eng. 54(11):5923–5936.

Wang CL, He BB, Hou XL, Li JY, Liu L. 2020. Stress-energy mechanism for rock failure evolution based on damage mechanics in hard rock. Rock Mech Rock Eng. 53(3):1021–1037.

Wang F, Kaunda R. 2019. Assessment of rockburst hazard by quantifying the consequence with plastic strain work and released energy in numerical models. Int J Min Sci Technol. 29(1):93–97.
Wang SR, Zhao YH, Zou ZS, Jia HH. 2017. Experimental research on energy release characteristics of water-bearing sandstone alongshore wharf. Pol Marit Res. 24(s2):147–153.

Wang QY, Zhu WC, Xu T, Niu LL, Wei J. 2017. Numerical simulation of rock creep behavior with a damage-based constitutive law. Int J Geomech. 17(1):04016044.

Xie HP, Li LY, Ju Y, Peng RD, Yang YM. 2011. Energy analysis for damage and catastrophic failure of rocks. Sci China Technol Sci. 54(S1):199–209.

Xu T, Zhou GL, Heap MJ, Yang SQ, Konietzky H, Baud P. 2018. The modeling of time-dependent deformation and fracturing of brittle rocks under varying confining and pore pressures. Rock Mech Rock Eng. 51(10):3241–3263.

Zhang MW, Meng QB, Liu SD. 2017. Energy evolution characteristics and distribution laws of rock materials under triaxial cyclic loading and unloading compression. Adv Mater Sci Eng. 2017:1–16.

Zhang QB, Zhao J. 2014. A review of dynamic experimental techniques and mechanical behavior of rock materials. Rock Mech Rock Eng. 47(4):1411–1478.

Zhou ZL, Li GN, Ning SL, Du K. 2014. Acoustic emission characteristics and failure mechanism of high-stressed rocks under lateral disturbance. Chin J Rock Mech Eng. 33(8):1720–1728.

Zhou GL, T X, Heap MJ, Meredith PG, Mitchell TM, Sesnic AS, Yuan Y. 2020. A three-dimensional numerical meso-approach to modeling time-independent deformation and fracturing of brittle rocks. Comput Geotech. 117:103274.

Zhu W, Li S, Li S, Niu L. 2019. Influence of dynamic disturbance on the creep of sandstone: an experimental study. Rock Mech Rock Eng. 52(4):1023–1039.

Zhu WC, Li S, Niu LL, Liu K, Xu T. 2016. Experimental and numerical study on stress relaxation of sandstones disturbed by dynamic loading. Rock Mech Rock Eng. 49(10):3963–3982.

Zhu W, Li Z, Zhu L, Tang C. 2010. Numerical simulation on rockburst of underground opening triggered by dynamic disturbance. Tunn Undergr Space Technol. 25(5):587–599.

Zhu WC, Tang CA. 2004. Micromechanical model for simulating the fracture process of rock. Rock Mech Rock Eng. 37(1):25–56.

Zhu WC, Wei CH, Li S, Wei J, Zhang MS. 2013. Numerical modeling on destress blasting in coal seam for enhancing gas drainage. Int J Rock Mech Min Sci. 59:179–190.

Zhu WC, Zuo YJ, Shang SM, Li ZH, Tang CA. 2007. Numerical simulation of unstable failure of deep rock tunnel triggered by dynamic disturbance. Chin J Rock Mech Eng. 26(5):915–921.