Dynamic mechanical properties of jointed soft rock samples subjected to cyclic triaxial loading: a FEM-DEM-based study

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Abstract. In order to investigate the fatigue behavior of jointed soft rock samples with different joint dip angles, cyclic triaxial tests under different stress amplitudes and confining pressures were numerically simulated using the combined finite-discrete element method (FEM-DEM). The dynamic strength and deformation rules were revealed, including the masing effect, the ratcheting effect, the volumetric strain properties and the failure modes influenced by joint dip angles. During the first hysteresis loop, the nonlinearity of the loading curve is much stronger than that in subsequent cycles, and the damage and deformation are almost the most, which demonstrates that the effect of stress history on soft jointed samples subjected to cyclic loading is great, especially the first loading cycle. When the applied static and dynamic maximum deviatoric stress are the same, the vertical compressive stress of the dynamic case is found to be lower than that of the static case, and the vertical tensile stress exists in some local position, which may be the reason why the cracks can increase and propagate gradually when the dynamic maximum stress is lower than the static strength.

1. Introduction
A large number of rock projects involve the rock masses, which always contain many discontinuities. The cyclic loads, such as the seismic load, train load and blasting load, greatly affect the mechanical behavior of rocks, which are different from the static properties. Even though some studies have been carried out on the cyclically dynamic properties of jointed rock masses,\textsuperscript{1,2} much work is still required to be done. Compared with experimental studies, numerical studies are convenient and inexpensive, and can simulate many complicated problems and reveal the internal failure mechanism. Most numerical studies on dynamic properties of rock materials are aimed at impact loads on Split Hopkinson Pressure Bar or Brazilian disc.\textsuperscript{3-4} While, numerical studies on rocks under cyclic loading are very lacking\textsuperscript{5,6} and all the more so for jointed rocks. Therefore, it is necessary to numerically study the dynamic mechanical
properties of jointed rock samples subjected to cyclic loading, which can help solve problems of fatigue deformation and reveal macro-meso dynamic failure mechanisms of jointed rocks.

Finite element method (FEM) and discrete element method (DEM) are the most common two numerical methods. FEM is rarely used in the rock damage and fracture problems, as its shortage of considering fracture and multiple cracks. DEM is used more frequently as it can model crack initiation and propagation, but it cannot consider the deformation of particles or blocks. As a result, the combined finite-discrete element method (FEM-DEM) was proposed. The continuous deformation is described by DEM, the discontinuous deformation is described by FEM, and the transition from continuity to discontinuity is realized by the fracture of joints and the breakage of elements.

Much work has been done on rock mechanics studies using FEM-DEM. Munjiza et al. proposed a crack initiation and crack propagation model for mode I loaded cracks and analyzed fracture problems of concrete with the model implemented in a combined finite/discrete element code. Using an innovative FEM-DEM research code, Mahabadi et al. studied the influences of confining pressure and displacement rate on a rock sample under laboratory triaxial compression test, and found that the FEM/DEM code was capable of capturing the brittle-ductile transition. Applying FEM-DEM, Lisjak et al. reproduced field observations where blocks break and the fragments accumulate along the slope, and assessed the stability of rock slopes subjected to seismic shaking by introducing absorbing boundary conditions. Yan et al. proposed a hydromechanical model, finite-discrete element method with fluid flow in three dimensions and validated it in dealing with five problems. Davide et al. presented FEM-DEM numerical analysis to characterize rock bridge strength in rock slopes. Apparently, FEM-DEM is appropriate to solve the deformation and damage problems of rocklike materials.

In general, numerical investigation on intact and jointed rocks subjected to cyclic loading are relatively lacking. And the dynamic deformation and failure mechanism of jointed rock samples under cyclic loading is still not very clear. Meanwhile, FEM-DEM is an excellent method to study rock mechanics. To grasp the dynamic properties and investigate the macro-meso breakage mechanism, serial numerical investigations on jointed soft rocks are accomplished. In this work, both intact and jointed soft rock samples with different joint dip angles are tested. Firstly, static triaxial tests are modelled and analyzed, then, cyclic triaxial tests under different confining pressures and different levels of stress amplitudes are numerically studied. Combined with experimental results, the macroscopic dynamic strength and deformation properties and mesoscopic breakage mechanism are systematically studied.

2. Modelling method

2.1. Numerical test scheme
Intact rock samples and jointed soft rock samples with joint dip angles of 30° and 45° are chosen to be tested under confining pressures ($\sigma_c$) of 100kPa, 200kPa and 400kPa. For dynamic tests, samples are subjected to cyclic loads with multiple levels of stress amplitudes respectively. The detailed numerical test scheme is shown in Table 1. During the modelling, spatial and temporal distributions of stress and deformation, cyclic numbers, deformation and failure characteristic, and so on, are monitored.
2.2. Model description

Experimental studies of jointed rock samples under cyclic loading have been conducted. Combining with the experimental studies, numerical models are established using the same geometric and physical parameters. The modelled samples of \(\phi 50\text{mm}\times 100\text{mm}\) are shown in figure 1, and a zero-thickness and cohesionless joint with a certain dip angle, which is located between the green elements and yellow elements, is set in the jointed soft rock sample. All elements are triangular element, and the intact sample contains 1268 elements and 692 nodes. Parameters used for calculating are shown in Table 2. During the loading process, the bottom loading platen is fixed and confining pressure is exerted on left and right sides. Vertical displacements or stress are applied on the top loading platen, for static numerical tests, it’s vertical displacement with the velocity of 0.5m/s, and for cyclic cases, it’s vertical cyclic stress with a sinusoidal waveform. As to the cyclic loads, multiple levels of dynamic maximum stresses (\(q_d^{max}\)), which is slightly lower than the static strength (\(q_0\)), are chosen in each case to study the influence of the maximum stress on the dynamic mechanical property of the jointed soft rock.

![Image](a) Intact sample (b) Jointed soft rock sample

Figure.1 The modelled samples

| Table 1 Calculational conditions and partial results |
|---------------------------------------------|
| \(\sigma_c (kPa)\) | 100 | 200 | 400 |
| \(q_s (MPa)\) | 1.5 | 2.43 | 4.03 |
| \(q_d^{max} (MPa)\) | 1.4 | 1.3 | 1.1 | - | 2.4 | 2.2 | 2.0 | 4.0 | 3.6 | 3.4 | - | - |
| \(N_f\) | 5 | 22 | 100 | - | 9 | 18 | 63 | 4 | 29 | 69 | - | - |
| \(\varepsilon^P_d (%)\) | 4.2 | 4.5 | 4.9 | - | 5.3 | 6.0 | 6.2 | 6.7 | 7.1 | 7.4 | - | - |
| \(\varepsilon^T_d (%)\) | 1.7 | 2.3 | 2.7 | - | 2.0 | 2.3 | 3.0 | 1.9 | 2.7 | 3.1 | - | - |

| Intact samples |
|----------------|
| \(\sigma_c (kPa)\) | 100 | 200 | 400 |
| \(q_s (MPa)\) | 1.46 | 2.37 | 3.61 |
| \(q_d^{max} (MPa)\) | 1.3 | 1.2 | 1.15 | 1.1 | 2.2 | 2.0 | 1.9 | 3.5 | 3.4 | 3.3 | 3.2 | 3.1 |
| \(N_f\) | 7 | 28 | 83 | 188 | 8 | 28 | 103 | 15 | 32 | 48 | 79 | 169 |
| \(\varepsilon^P_d (%)\) | 4.4 | 5.5 | 6.1 | 7.1 | 4.8 | 6.0 | 5.3 | 6.1 | 6.3 | 6.9 | 7.1 | 6.9 |
| \(\varepsilon^T_d (%)\) | 2.0 | 3.5 | 3.6 | 3.9 | 1.8 | 2.5 | 2.7 | 2.0 | 2.4 | 2.7 | 2.8 | 2.9 |

| 30° samples |
|----------------|
| \(\sigma_c (kPa)\) | 100 | 200 | 400 |
| \(q_s (MPa)\) | 0.856 | 1.48 | 2.6 |
| \(q_d^{max} (MPa)\) | 0.84 | 0.82 | 0.82 | - | 1.4 | 1.3 | 1.2 | 2.3 | 2.1 | 1.9 | - | - |
| \(N_f\) | 3 | 26 | 156 | - | 6 | 51 | 148 | 7 | 58 | - | - | - |
| \(\varepsilon^P_d (%)\) | 5.5 | 4.7 | 5.6 | - | 5.7 | 6.4 | 7.7 | 6.4 | 6.9 | - | - | - |
| \(\varepsilon^T_d (%)\) | 3.7 | 3.2 | 4.2 | - | 3.7 | 4.3 | 5.5 | 3.4 | 4.0 | - | - | - |

| 45° samples |
|----------------|
| \(\sigma_c (kPa)\) | 100 | 200 | 400 |
| \(q_s (MPa)\) | 1.5 | 2.43 | 4.03 |
| \(q_d^{max} (MPa)\) | 1.4 | 1.3 | 1.1 | - | 2.4 | 2.2 | 2.0 | 4.0 | 3.6 | 3.4 | - | - |
| \(N_f\) | 5 | 22 | 100 | - | 9 | 18 | 63 | 4 | 29 | 69 | - | - |
| \(\varepsilon^P_d (%)\) | 4.2 | 4.5 | 4.9 | - | 5.3 | 6.0 | 6.2 | 6.7 | 7.1 | 7.4 | - | - |
| \(\varepsilon^T_d (%)\) | 1.7 | 2.3 | 2.7 | - | 2.0 | 2.3 | 3.0 | 1.9 | 2.7 | 3.1 | - | - |

| \(\sigma_c (kPa)\) | 100 | 200 | 400 |
| \(q_s (MPa)\) | 1.46 | 2.37 | 3.61 |
| \(q_d^{max} (MPa)\) | 1.3 | 1.2 | 1.15 | 1.1 | 2.2 | 2.0 | 1.9 | 3.5 | 3.4 | 3.3 | 3.2 | 3.1 |
| \(N_f\) | 7 | 28 | 83 | 188 | 8 | 28 | 103 | 15 | 32 | 48 | 79 | 169 |
| \(\varepsilon^P_d (%)\) | 4.4 | 5.5 | 6.1 | 7.1 | 4.8 | 6.0 | 5.3 | 6.1 | 6.3 | 6.9 | 7.1 | 6.9 |
| \(\varepsilon^T_d (%)\) | 2.0 | 3.5 | 3.6 | 3.9 | 1.8 | 2.5 | 2.7 | 2.0 | 2.4 | 2.7 | 2.8 | 2.9 |
Table 2 Parameters for numerical simulation

| Parameter for element | Young’s modulus | Poisson’s ratio | Density | Friction coefficient | Tangential contact penalty | Normal contact penalty |
|-----------------------|-----------------|-----------------|---------|---------------------|--------------------------|------------------------|
|                       | 100MPa          | 0.25            | 2100kg/m^3 | 0.6                | 4e7Pa                    | 4e8Pa                  |
| Parameter for crack element | Tensile strength | Fracture penalty | Internal cohesion | Internal friction coefficient | Fracture penalty | - |
|                       | 230kPa          | 20g/s^2         | 230kPa   | 0.75                | 3e9Pa                    | -                      |

3. Results and analysis

3.1. Dynamic triaxial test results

Numerical calculating is terminated when the axial strain reaches 16%. In the cyclic testes, the samples fail when the vertical displacements increase dramatically. The basic calculating results of all intact and jointed soft rock samples are shown in Table 1. It can be found that, the cyclically strengths are all lower than static strength when the joint dip angle and confining pressure are the same. The number of cycles at failure ($N_f$) decreases with increasing maximum stress. Generally, the cyclically dynamic strength decreases with increasing joint dip angles, and increases with increasing confining pressure.

Figure 2 presents the static stress-strain curves and volumetric strain-axial strain curves under different confining pressures and at different joint dip angles. When subjected to static loading, stress-strain curves of all jointed soft rock samples exhibit strain softening behavior. The jointed soft rock samples under static loading compact with relatively small volumetric strains and then dilate up to failure with relatively large volume expansions. Both the strength and volumetric shrinkage increase with increasing confining pressures, and the volume expansions decrease with increasing confining pressures. The strengths of intact samples are the highest under the same confining pressure and for 45˚ cases it’s the lowest. The difference of strengths of between intact samples and 30˚ samples is small when the confining pressure is small, while becomes significant when the confining pressure is large. When the confining pressure is the same, the volumetric shrinkage of the 45˚ samples is the smallest. Differently, the stress-strain curves of samples with joint dip angles of 45˚ have an obvious inflection point before the peak strength, after which point the slopes of curves decrease largely and the deformation becomes much faster. It can be seen that, this is because the joint slides along the joint plane for the 45˚ case. All these phenomena agree well with the laboratory experiments. 14

![Graph](a) the 30˚ jointed soft rock samples

![Graph](b) the 45˚ jointed soft rock samples
loop is much larger obviously. The hysteresis loops in the initial portion of the stress-strain curves are sparse, then they are dense, and before failure they are sparse again. Particularly, the residual strain during the first hysteresis amplitude. The hysteresis loops exhibit cyclic softening behavior with increasing plastic or irreversible axial strain for the constant stress amplitude. The strengths under cyclic loading are all lower than corresponding static strength, and the numbers of cycles at failure increase with the decreasing of maximum stress. The higher maximum stress is closer to the static strength, this indicates the failure occurs more easily, hence the numbers of cycles at failure decrease with increasing joint dip angles, particularly for the 45° case they decrease obviously. The static stress-strain curves and volumetric strain-axial strain curves of joint dip angles of 30°, 45°, and 60° are presented in Figure 2, 3, and 4 respectively. It can be found from Table 1 that, within the scope of given confining pressures and joint dip angles, the deformation grows still so rarely that samples are hard to be damaged. This agrees well with the excitation force threshold phenomena founded of cyclic loading.

3.2. Strength properties

It can be found from Table 1 that, within the scope of given confining pressures and joint dip angles, the strength or cyclic dynamic strength, they all increase with increasing confining pressures and decrease with increasing joint dip angles, particularly for the 45° case they decrease obviously. The static stress-strain curves and volumetric strain-axial strain curves of joint dip angles of 30°, 45°, and 60° are presented in Figure 2, 3, and 4 respectively. It can be found from Table 1 that, within the scope of given confining pressures and joint dip angles, the deformation grows still so rarely that samples are hard to be damaged. This agrees well with the excitation force threshold phenomena founded of cyclic loading.
Figure 6 presents the relationships between the maximal deviator stress and the number of cycles at failure at different joint dip angles and under different confining pressures. It can be observed that, the dynamic strength increases with increasing confining pressures at the same joint dip angle; when the confining pressures are the same, the dynamic strengths of the jointed soft rock samples are lower than that of the intact samples, especially the 45° case; the number of cycles at failure decreases with increasing maximal deviator stress at the same joint dip angles and under the same confining pressures.

The stress ratio $R_s$, which is equal to the ratio of the static triaxial strength to the maximum stress of the cyclic loading, is defined to describe the influences of both the maximum stress and strength of the sample. Figure 7 presents the relationship between $R_s$ and the common logarithm of the number of cycles at failure for different joint dip angles and under different confining pressures. These demonstrate that the number of cycles at failure decreases with increasing stress ratios for all samples with different joint dip angles and confining pressure. Basically, the stress ratios of sample which failed are between 0.7 and 1.0. These indicate that the stress ratio, rather than only the maximum stress or the static strength influenced by confining pressures and joint dip angles, is the key index that determines the fatigue life of jointed soft rock samples. Stress ratios can comprehensively reflect the influences of joint dip angles, confining pressures and maximum stress. Higher stress ratios indicate the maximum stress is closer to the static strength, hence the samples failed more easily, and the numbers of cycles at failure are fewer.

3.3. Deformational properties

It can be found from figures 3-5 that both intact and jointed soft rock samples exhibit cyclic softening behavior with increasing plastic or irreversible axial strain for the constant stress amplitude. As a whole, all samples under cyclic loading dilate continually up to failure. The hysteresis loops in the initial portion of the cyclic loading are sparse, then they are dense, and lastly near failure they are sparse again. The residual strain during the first hysteresis loop is much larger obviously. In particular for all the 45° case, the residual strain of the initial several hysteresis loops is relatively large, that is because the joint dip angle is relatively large and the failure mode is different from other jointed soft rock samples; it was observed from the modelling process that, the 45° samples slide along the joint plane in the early stage.

In each loading and unloading cycle, the secant modulus of the hysteresis loop can get from the starting point of the loading stage to the starting point of the unloading stage in the deviatoric stress-
axial strain curves. It can be found from figures 3-5 that, in each group of cyclic loading test, the secant modulus of the first hysteresis loop is much smaller than that in subsequent cycles, and the secant modulus difference of the adjacent hysteresis loop in subsequent cycles is smaller than that of the first two cycles; only the nonlinearity of the loading curve in the first hysteresis loop is strong, while the nonlinearity of the loading curve and unloading curve is much weak relatively after the first loading curve and before samples failed; these demonstrate that during the loading process of the first hysteresis loop, the damage and deformation in samples are the most before failure, and the nonlinearity are the strongest, after the first loading stage, the fracture and damage generated in loading and unloading cycles are much smaller. However, although the fracture and damage generated in each subsequent hysteresis loop are very small, the fracture and damage can accumulate continually under the continuous cyclic loading, the deformation of samples becomes larger continually and at last the samples still fail, and this is why samples can fail under cyclic loading when the maximum stress is lower than the static strength.

Table 1 presents the peak axial strain $\varepsilon_{p}$ and residual axial strain $\varepsilon_{r}$ at failure for three groups of samples under different confining pressures and different maximum stress. In general, when the joint dip angle and the confining pressure are the same, the peak axial strain and residual axial strain at failure increase with the decreasing of the maximum stress.

The residual axial strain-loading time curves for jointed soft rock samples at different confining pressures and different maximum stress are presented in Figures 8-10, in which the residual strain is defined as the axial strain at which the axial stress reaches the minimal value in a cycle after N cycles. It can be found that, for all samples, especially the samples failing with large number of cycles, the axial strain increases rapidly in the initial cyclic stage, then increases slowly at a steady speed for a long time, and finally increases rapidly before failure. With the number of cycles increases, the amplitude of the axial strain increases gradually and slowly until the samples fail. When the maximum stress is large relatively, the residual axial strain and peak axial strain increase rapidly and the numbers of cycles at failure are few. The most special is the first cycle, in which the increments of the residual axial strain are much larger than that in cycles before failure; this demonstrates that the first loading is very important in its stress history of the jointed and intact samples subjected to cyclic loading, the damage and deformation caused by the first loading are much larger than that caused by the same stress levels in the subsequent cycles. In the 45° case, the residual axial strain of the first cycle is much larger than that of intact and 30° samples, and its axial strain-time curve has an abrupt increasing in the initial stage, the reason for the former is related to the slip of the samples along the 45° joint plane, and the latter is related to the fracture which dips towards the opposite direction to the joint plane, and these can be obviously observed during the modelling process.

Figure 8 The residual axial strain-time curves for 30° samples ($\sigma_z=400$ kPa)

- (a) maximum stress of 3.5MPa
- (b) maximum stress of 3.3MPa
- (c) maximum stress of 3.1MPa

Figure 9 The residual axial strain-time curves for 30° samples at confining pressure of 100kPa

- (a) maximum stress of 1.3MPa
- (b) maximum stress of 1.2MPa
- (c) maximum stress of 1.1MPa
The deformation and cracks propagation under cyclic loading can be reflected well. Volumetric strain of the rock samples under cyclic loading can be modelled very well, and the samples’ volumetric strain curves synthetically reflect the volumetric deformation property caused by samples’ deformation and cracks propagation under cyclic loading. These demonstrate that the change rule of the volumetric strain of the rock samples under cyclic loading can be modelled very well, and the samples’ deformation and cracks propagation under cyclic loading can be reflected well.

Figure 10 The residual axial strain-time curves for 45˚ samples (σc=100 kPa)

Figure 11 presents the dynamic stress-strain curves and volumetric strain curves for intact rock samples at confining pressure of 100kPa. It can be found that the samples under cyclic loading compact with relatively small volumetric strains and then dilate up to failure with relatively large volume expansions. The sudden increase of the volumetric strain is found in the intermediate stage in Figure 11 (c), and this is caused by the relatively large crack propagation in this moment. The volumetric strain-axial strain hysteresis loops are very evident. With the increasing cyclic numbers, the volume varies with the forms between bulk shrinkage and volume expansion unequally and repeatedly. The evolution laws of the volumetric strain exhibit three stages, which are similar with that of the axial strain. These volumetric strain curves synthetically reflect the volumetric deformation property caused by samples’ deformation and cracks propagation under cyclic loading. These demonstrate that the change rule of the volumetric strain of the rock samples under cyclic loading can be modelled very well, and the samples’ deformation and cracks propagation under cyclic loading can be reflected well.

Figure 11 Dynamic stress-strain curves and volumetric strain curves for intact samples (σc=100 kPa)

3.4. Deformation and failure mechanism

Figure 12 present the deformation pattern of samples under cyclic loading at different moments. It can be found that, the intact samples deform obviously after the first cycle; in the intermediate stage the deformation occurs gradually and slowly and the cracks are few relatively; when approaching failure intact samples deform quickly and plenty of cracks appear. For the 30˚ case, its deformation and failure characteristics are similar with the intact samples, and basically the deformation along the joint plane are not observed. For the 45˚ case, in the initial stage, the samples slide down along the joint plane; in the intermediate stage, samples deform slowly and the cracks increase slowly, the deformation occurs mainly around the joint plane, and the direction of the deformation is mainly parallel to the joint plane;
during the stage approaching failure, the deformation around the joint plane is large, and the deformation which dips towards the opposite direction to the joint plane is also large. Figure 13 presents the horizontal displacement-loading time curves of the nodes around the joint plane. It can be found that, before approaching failure, the horizontal displacements of the nodes above the joint plane occur towards the left, and for the nodes below the joint plane they occur towards the right; while, during the failure stage, for the nodes below the joint plane on the left side, the displacements change towards left, and for the nodes above the joint plane on the right side, the displacements change towards right. These agree well with the deformation evolutionary character of the samples with joint dip angle of 45˚ in Figure 12(c), in which the direction of the deformation is mainly parallel to the joint plane before approaching failure, and the deformation which dips towards the opposite direction to the joint plane becomes large when approaching failure.

Figure 12: The deformation pattern of different samples under cyclic loading
Figure 13 presents the horizontal displacement-loading time curves of the nodes around the joint plane. Figure 14 presents the nephograms of vertical stress. For the dynamic case, the nephograms come from the moment when the cyclic stress is equal to the maximum stress, and for the static case, the moment is when the static deviatoric stress is equal to the dynamic maximum stress. When the deviatoric stress are the same, the vertical stress of the dynamic case is lower than the static case, and tensile stress exists in some local position, in other words, compressive stress of the dynamic case is lower, the tensile stress and cracks exist more easily. Therefore, although the maximum stress of the dynamic case is lower than the static strength, the cracks increase and propagate gradually with the increasing of the cycles, at last the samples can still fail. The reason could be that, stress concentration exists more easily or the degree of stress transferring is smaller in the jointed soft rock samples subjected to cyclic loads.

(a) on the left side of joint plane
(b) on the right side of joint plane

Figure 14 The horizontal displacement-loading time curves of the nodes around the joint plane
4. Conclusions
The dynamic properties of jointed soft rock samples under cyclic loading can be well captured using FEM-DEM, and some important conclusions are found from the macro-meso and multiscale perspective:

The dynamic strength and numbers of cycles at failure can reflect the effects of the confining pressure, joint dip angles and the maximum stress. The number of cycles at failure decreases with increasing stress ratios for all samples with different joint dip angles and confining pressure. Basically, the stress ratios of samples which failed are between 0.7 and 1.0, for samples with stress ratios lower than certain values they are hard to fail, which agrees well with the excitation force threshold phenomena.

Both intact and jointed soft rock samples exhibit cyclic softening behavior with increasing plastic or irreversible axial strain for the constant stress amplitude, and all samples under cyclic loading compact with relatively small volumetric strains and then dilate up to failure with relatively large volume expansions. The stress-strain hysteretic loop, the volumetric strain-axial strain hysteretic loop and the axial strain-time curves all exhibit the three-stage laws when the maximum stress level is medium. In general, when the joint dip angle and the confining pressure are the same, the peak axial strain and residual axial strain at failure increase with the decreasing of the maximum stress. The axial strain amplitudes increase gradually with the increasing of time. The dynamic stress-strain curves, the axial strain-time curves and the volumetric strain-axial strain curves can reflect the effects of the generation of cracks and the joint dip angles, such as the slip of samples along the 45° joint plane. The nonlinearity of the loading curve in the first hysteresis loop is much stronger than that in subsequent cycles, and the secant modulus is much smaller; these demonstrate the great effect of stress history on jointed samples.

The total processes from the initiation and propagation of microcracks to the final failure are reproduced. The dynamic failure modes and the effects of joint dip angles on the failure modes are revealed from the macro-meso and multiscale perspective. When the applied deviatoric stress are the same, the compressive stress of the dynamic case is lower, and the tensile stress and cracks exist more easily; therefore, although the maximum stress of the dynamic case is lower than the static strength, the cracks increase and propagate gradually with the increasing of the cycles until fail.

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References
[1] Liu EL, Huang RQ, He SM. Effects of frequency on the dynamic properties of intact rock samples subjected to cyclic loading under confining pressure conditions. Rock Mech Rock Eng. 2012;45(1):89-102.
[2] Li YC, Wu W, Tang CA, Liu B. Predicting the shear characteristics of rock joints with asperity degradation and debris backfilling under cyclic loading conditions. Int J Rock Mech Min Sci. 2019;120: 108-118.
[3] Imani M, Nejati HR, Goshtasbi K. Dynamic response and failure mechanism of Brazilian disk specimens at high strain rate. Soil Dyn Earth Eng. 2017;100: 261-269.

[4] Saksala T, Jabareen M. Numerical modeling of rock failure under dynamic loading with polygonal elements. Int J Numer Anal Met. 2019;43(12): 2056-2074.

[5] Pouya A, Zhu C, Arson C. Micro–macro approach of salt viscous fatigue under cyclic loading. Mech Mater. 2016;93:13-31.

[6] Song ZY, Konietzky H, Herbst M. Bonded-particle model-based simulation of artificial rock subjected to cyclic loading. Acta Geotech. 2019;14(4): 955–971.

[7] Munjiza A. The combined finite-discrete element method. Chichester: John Wiley & Sons, Ltd; 2004.

[8] Munjiza, A, Andrews KRF, & White JK. Combined single and smeared crack model in combined finite-discrete element analysis. Int J Numer Meth Eng. 1999;44(1): 41-57.

[9] Mahabadi OK, Lisjak A, Grasselli G, et al. Numerical modelling of a triaxial test of homogeneous rocks using the combined finite-discrete element method. Proceedings of ISRM Rock Mechanics Symposium, Lausanne; 2010.

[10] Lisjak A, Grasselli G. Combined finite-discrete element analysis of rock slope stability under dynamic loading. Proceedings of 2011 Pan-Am CGS geotechnical conference, 2011.

[11] Yan CZ, Zheng H. Three-dimensional hydomechanical model of hydraulic fracturing with arbitrarily discrete fracture networks using finite-discrete element method. Int J Geomech. 2016;17(6):04016133.

[12] Davide E, Davide D, Doug S. Challenges in the characterisation of intact rock bridges in rock slopes. Eng Geol. 2018;245: 81-96.

[13] Liu MX, Liu EL. Dynamic mechanical properties of artificial jointed rock samples subjected to cyclic triaxial loading. Int J Rock Mech Min Sci. 2017;98: 54-66.

[14] Liu MX, Liao MK, Liu EL, et al. Experimental Research on Mechanical Properties of Jointed Rock Mass with Different Angles of Inclination. J B Univ Technol. 2018;44(3):336-343.