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Core discing characteristics and mitigation approach by a novel developed drill bit in deep rocks

ZHENG Min-zong(郑民总)[1, 2], LI Shao-jun(李邵军)[1], YAO Zou(姚邹)[3],
ZHANG Ao-dong(张奥东)[3], XU Ding-ping(徐鼎平)[1], ZHOU Ji-fang(周济芳)[4]

1. State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. Faculty of Engineering, China University of Geosciences, Wuhan 430074, China;
4. Yalong River Hydropower Development Co., Ltd., Chengdu 610051, China

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Abstract: Core discing often occurs in deep rocks under high-stress conditions and has been identified as an important characteristic for deep rock engineering. This paper presents the formation mechanism of core discing firstly. Then, the interaction between diamond drill bits and rock was analyzed based on numerical modeling. A novel drill bit with an inner conical crown for the mitigation of core discing was designed and verified by simulation experiments. The mitigation method was applied in the cavern B1 of CJPL-Ⅱ and satisfactory results had been achieved. The percentage of core discing had been obviously decreased from 67.8% when drilling with a rectangular crown drill bit, to 26.5% when an inner conical crown drill bit had been adopted. This paper gives full insight into core discing characteristics and provides a new method for core discing mitigation; it will potentially contribute to stress measurement in deep rock engineering.

Key words: core discing; mitigation; drill bit crown; deep rocks; in-situ stress measurements

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1 Introduction

Core discing refers to an engineering geological phenomenon in which the core is broken into discs or fragments [1], as shown in Figure 1. It is a type of rock failure caused by geological actions and external disturbances during the process of core drilling under deep burial depth and high stress environmental conditions. Many researchers have attempted to analyze the characteristics and mechanism of the occurrences of core discing through laboratory testing, site observations and numerical analysis [2−6]. The interest in this phenomenon lies in the estimation of the in-situ stress from the shape and frequency of the failures along the core axis [7]. It was assumed that core discing may involve tensile failures, a combination of shear and tensile failures, or only shear failures.

LIM et al [8] studied the relationship between in-situ stress and core discing for Lac du Bonnet granite and believed that the magnitude and direction of the stress had certain influences on the core disc thicknesses. KANG et al [9] used a

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Corresponding author: LI Shao-jun, PhD, Professor; Tel: +86-27-87198805; E-mail: sjli@whrsm.ac.cn; ORCID: https://orcid.org/0000-0002-9956-0205

boundary element model to discuss the characteristics of induced stress and failures initiated by tensile stress. And then put forward an initiation criterion of core discing, along with an estimation procedure for rock stress. However, it was argued that discing was only an indicator of high stress and that simply estimating in-situ stress from fracture observations was inaccurate because core discing involved complex mechanical mechanisms. Unless only very crude stress estimate is required, it is not possible to estimate the in-situ stress by observing the rock cores [6]. The over-coring stress relief method [10−13] has developed into a mature technology in in-situ stress measurement. However, the core discing actions will potentially cause major difficulties for the measurement of in-situ stress when using over-coring stress relief methods. This is due to the fact that such methods require that the cores where the measuring instruments are placed to maintain certain integrity during the drilling process [3].

Figure 1 Typical core discing under high in-situ stress in Jinping deep tunnels

In order to solve the problem mentioned above, this paper first presented the formation mechanism of core discing. Then, a new core discing mitigation approach was introduced, in which the changing of the drill bit crown structure was developed based on the results of numerical simulations. The effects of different crown shapes were discussed based on LS-DYNA and FLAC^{3D}, and field tests were carried out in the marble of the CJPL-Ⅱ Laboratory in order to test the developed drill bit. Discussions were made on the potential application of this method in mitigating core discing during the deep rock in-situ stress measurement processes. The conclusions reached in this study have certain significance to the further understanding of the phenomenon of core discing and its mitigation.

2 Formation mechanism of core discing and potential mitigation approach

The long deep tunnels in Jinping II hydropower station are very famous in the world and have the maximum overburden amounting to 2525 m [14, 15]. Core discing occurred frequently during borehole drilling in the deeply buried test tunnels along the auxiliary tunnel [16−18]. It is a form of rock fracture, occurs under the combined actions of deep geological environment and external excavation disturbances, which is closely related to rock excavation and drilling [7].

Figure 2 shows the formation mechanism of core discing during drilling activities. The mechanism can be divided into two processes: core crack propagation and fracturing into discs. Drilling activity is the stress relief for the borehole wall. During the adjustment of local stress field, the borehole is subjected to radial compression and axial tension. Stress concentration tends to occur at the core roots which are in contact with the crown surface of a drill bit [19, 20]. When the stress concentration reaches the failure strength of rock, the core began to crack around tiny defects on the core surface. After the crack starts, the stress in the core root is concentrated and transferred to the crack tip. At the same time, the core will be gradually separated from the surrounding rock. The core will compressed in the radial direction and stretched in the axial direction, which causes cracks to expand toward the middle of the core. Finally, the fracture plane with a certain convex surface is formed by tensile fracture. Then, as the drill continues to drill in a downward direction, the same cycle will occur again. A stress concentration zone will build at the core roots and crack propagation will occur, resulting in the formation of another disced core.

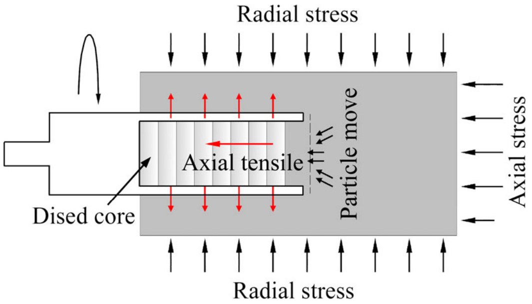


Figure 2 Core discing formation mechanisms during drilling process

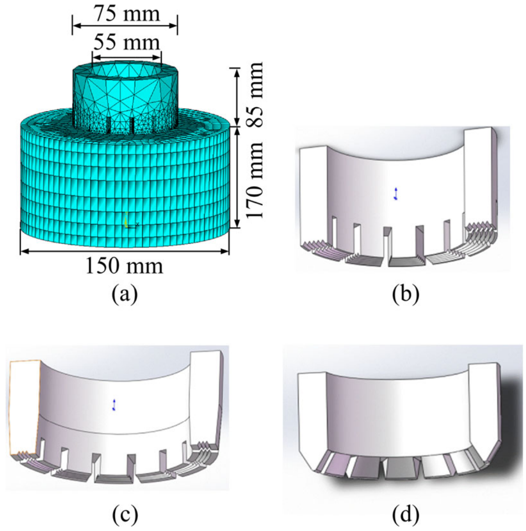
In summary, the continuous drilling activity is the fundamental reason that causes the core to break into discs periodically. When coring occurs, the slower the drilling speeds is, the longer the duration of the crack propagation will be, and the more obvious the disturbance effects of the drill pipe strings on the core will be. These effects will facilitate the cracks to expand through the rock core and produce disced cores. Therefore, in order to reduce the phenomenon of core discing, it is necessary to reduce core cracks during drilling, which can potentially lead to core discing.

Drill bit is the main tool for breaking rock during drilling [21]. The commonly used shapes of diamond drill bit crowns include rectangles, trapezoids, circles, cones, and so on. The different crown shapes have different contact modes with rock, and the stress and strain distributions on the rock also tend to be different. These differences will affect the generation and expansions of cracks and may lead to core discing. Therefore, in order to mitigate the core discing during drilling, a reasonable diamond drill bit crown structure will be an effective method.

3 Dynamic simulation of interaction between rock and drill bits

3.1 Numerical models

In order to study the interaction mechanism between rock and diamond drill bits, this study selected three common diamond drill bits with different crown shapes for dynamic drilling simulation, including rectangular crown, trapezoid crown and biconical crown. The nonlinear dynamic analysis software LS-DYNA based on finite element method was used to simulate the dynamic interaction between rock and drill bits. The numerical model of rock and drill bit, as well as three 3D models of the impregnated diamond drill bits with different crown shapes are shown in Figure 3. A contact mode was set between the drill bits and the rock as a surface-surface erosion contact algorithm. The friction coefficients were set as follows: static friction coefficient 0.35, dynamic friction coefficient 0.25. The bottom surface of rock limited its freedom in the vertical direction, while lateral boundary of the rock set the degree of freedom as zero. The drill bits were applied a constant vertically downward load along the drilling direction, and an initial speed of uniform rotation was applied. The plasticity and failure strain of rock were taken into account, and the drill bits were considered to be elastomeric. The material properties of the drill bits and rock are shown in Table 1.



(a) (b)

(c) (d)

Figure 3 Numerical models of rock and drill bits: (a) Interaction model of drill bit and rock; (b) Bit with rectangular crown; (c) Bit with trapezoid crown; (d) Bit with biconical crown

Table 1 Material properties of rock and drill bit

Parameter	Rock	Drill bit
Poisson ratio	0.27	0.3
Density/(kg·m^{-3})	2630	7830
Elastic modulus/GPa	55	207
Yield strength/MPa	117	
Shear modulus/MPa	4000	
Failure stain/%	0.06	

3.2 Stress analysis

Figure 4 shows von Mises stress distribution in rock caused by different drill bit: bit with the rectangular crown (Figure 4(a)); bit with the trapezoid crown (Figure 4(b)) and bit with the biconical crown (Figure 4(c)). Von Mises stress can represent the level of stress distribution. As we can see, after the contact with drill bit, the stress generated inside the rock will not be evenly distributed and stress concentration will occur at the contact positions. The degrees of stress concentration in rock were different with different drill bits. As shown in Figure 4, the maximum stress in rock caused by rectangular crown bit was

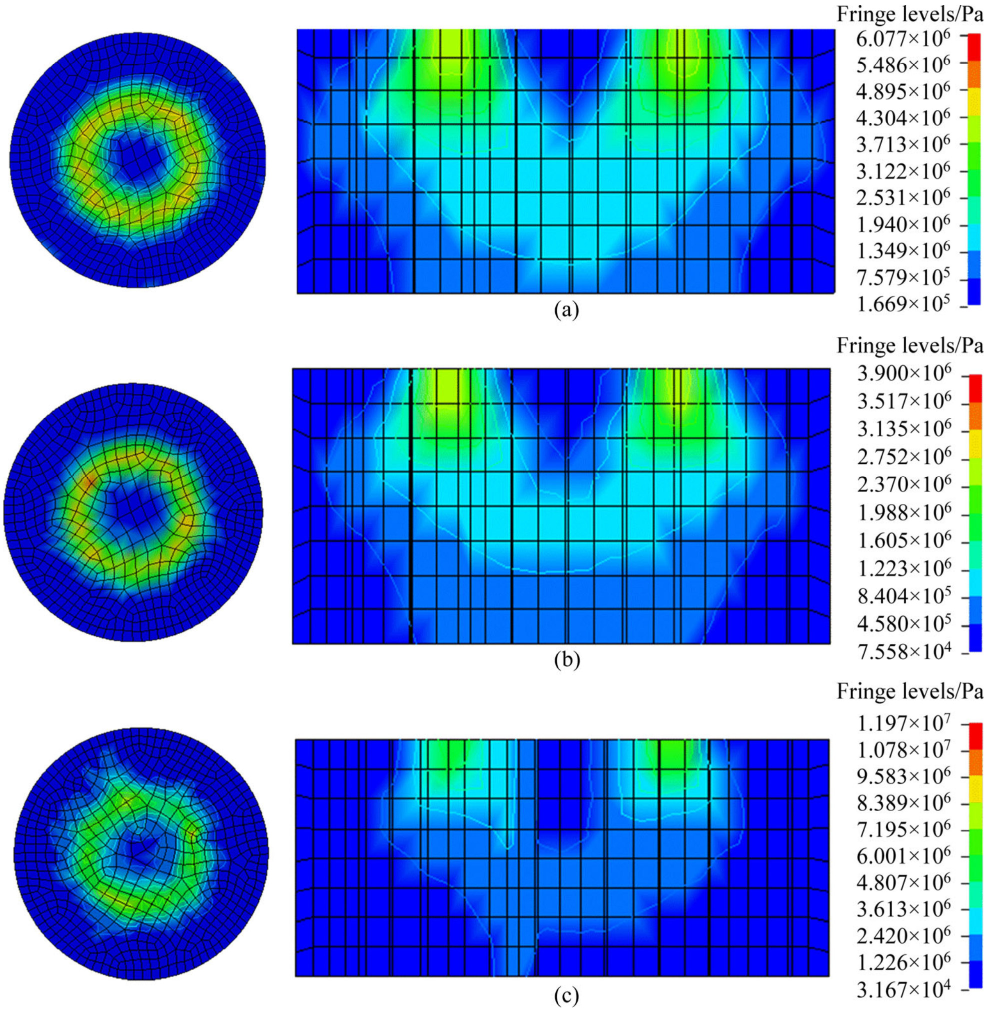


Figure 4 Von Mises stress distributions after drill bit contact with rock: (a) Bit with rectangular crown; (b) Bit with trapezoid crown; (c) Bit with biconical crown

6.07 MPa, while the maximum stress caused by the other drill bits were 3.9 and 11.97 MPa, respectively. The maximum stress in rock caused by drill bits with biconical crown was largest, so the drilling efficiency and drilling speeds will be high, which are conductive to mitigate the core discing. However, the high stress concentration also may lead to the core surface cracking, which then provided the conditions for core discing. Therefore, while improving drilling efficiency, the disturbance of drill bit to the core should be minimized as far as possible.

3.3 Scheme determination of inner conical crown

Based on the stress analysis mentioned above, the drill bit with conical crown has the high drilling efficiency. Therefore, the current study continued to use different conical crown drill bits to simulate the stress distribution of rock during drilling and to find the most suitable crown structure with fewer disturbances to the core. As shown in Figure 5, the von Mises stress distribution after dynamic contact between rock and three conical crown drill bits were simulated. Steps I, II and III were three drilling stages, which showed that the stress distributions when the rock was drilled to a depth of 0.1, 10 and 20 mm, respectively. It could be seen in the simulation results that three types of drill bits were found to have produced similar stress in the rock. However, the biconical crown drill bit (Figure 5(a)) was determined to have the maximum stress in the middle section of the rock core and was most likely to damage the core. The core was also be disturbed in core when using the outer conical crown drill bit (Figure 5(b)). And the stress in rock core drilling with the inner conical crown bit (Figure 5(c)) is maintained at a low level. The possible reason for this result was that the contact areas between the inner conical crown drill bit (Figure 5(c)) and the rock core were observed to

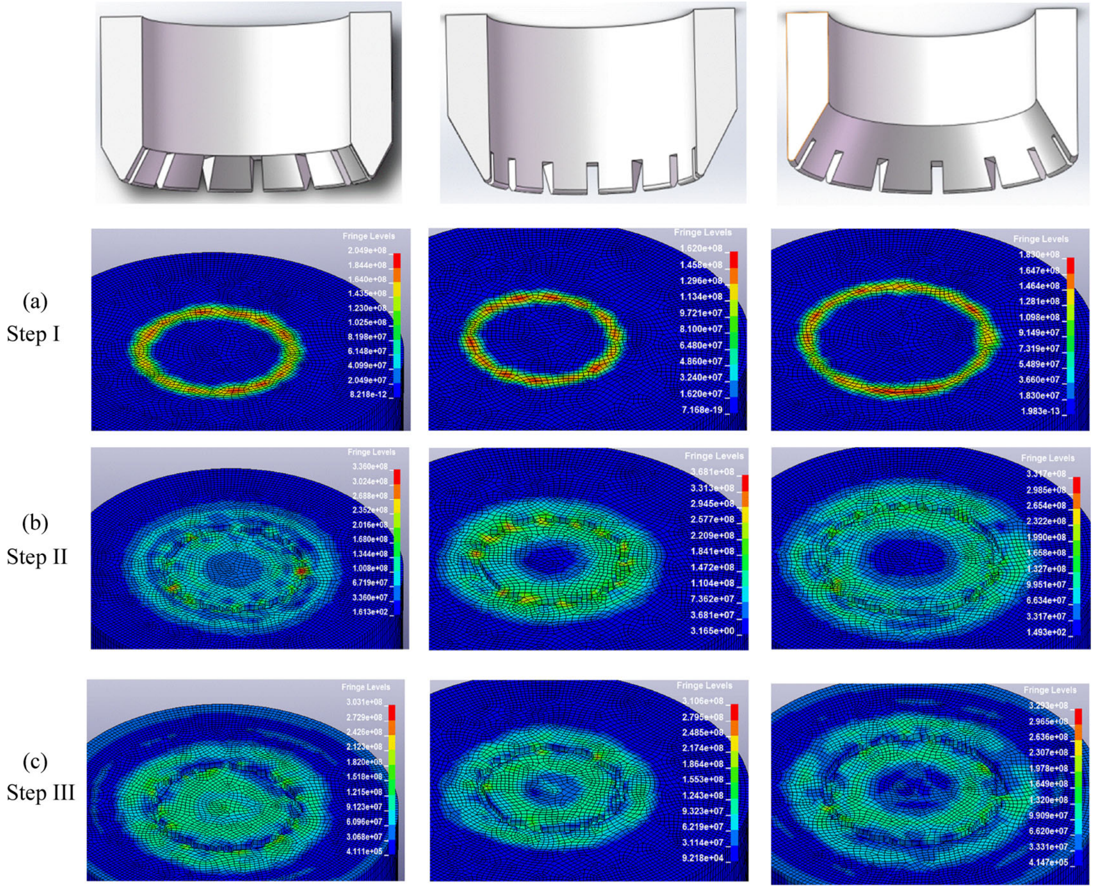


Figure 5 Von Mises stress distributions during the drilling process with the three different conical crowns: (a) Bit with biconical crown; (b) Bit with outer conical crown; (c) Bit with inner conical crown

gradually increase during the simulated drilling activities. As a result, the stress in the core had a more sufficient release and evolution time compared with other drill bits, and the core had been less affected.

According to the above simulated results, the inner conical crown drill bit (Figure 5(c)) have high drilling efficiency and also little disturbance to the core during drilling, which are both favorable factors for mitigating core discing. Thus, from the perspective of drill bit selection, the inner conical crown drill bit was a more ideal choice than the other drill bits to avoid the core fracturing into discs, and should be taken into consideration in practical application for mitigating core discing.

4 Validation of core discing mitigation with an inner conical crown drill bit

4.1 Validation by numerical analysis

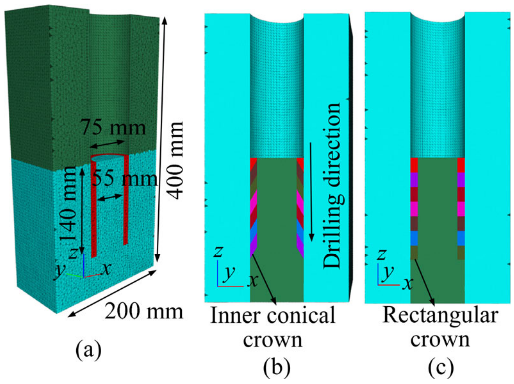
4.1.1 Model

Following the defining of the different wear shapes to reflect the different crown shapes of the drill bits, the drilling processes were simulated for the purpose of evaluating the influences of the different drill bits on a core under high in-situ stress [22]. FLAC^{3D} software was used to simulate the whole process of coring. Note that core discing is a kind of failure in rock. The Mohr-Coulomb strain softening/hardening model was adopted in order to simulate the post-failure behavior of geomaterials [6, 23−25]. The rock mass parameters of Jinping marble used in the constitutive model were shown in Table 2, which was obtained from the uniaxial tensile and triaxial compression test [26]. Since the elasto-plastic model was adopted, the relationship between strain and stress model is nonlinear and stress path dependent, the coring process was modeled step by step.

The 3D geometric model is shown as Figure 6(a). The drilling process was simulated by nulling the elements in red section from a zero core stub length to 140 mm using a stub length increment of 20 mm. The inner conical crown drill bit was adopted according to the above analysis, and the rectangular crown drill bit was also

Table 2 Strain softening parameters used in FLAC^{3D}

Plastic strain/%	Elastic modulus/GPa	Poisson ratio	Cohesion/MPa	Friction angle/(°)	Tension/MPa
0	43	0.25	45	38	9.1
0.5	43	0.25	26	43	4.5
0.7	43	0.25	18	50	0.5
1.0	43	0.25	10	50	0.5
1.5	743	0.25	6	50	0.5



(a) (b) (c)

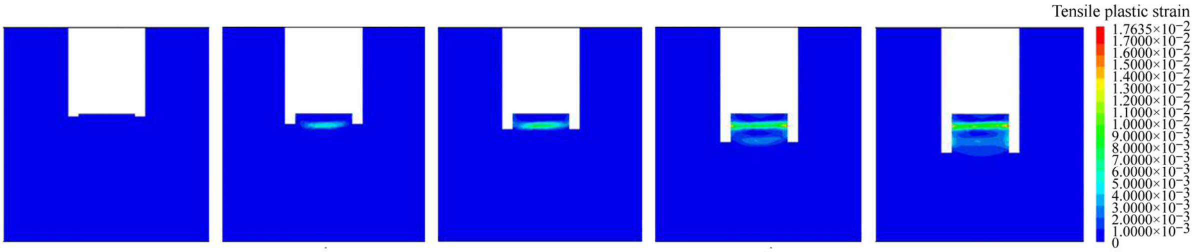
Figure 6 Numerical simulation model, all dimensions in mm: (a) Profile of 3D model and dimension, (b) Model drilled with inner conical crown drill bit; (c) Model drilled with rectangular crown drill bit

simulated for contrast purposes. Figure 6(b) shows an inner cone and Figure 6(c) is rectangle. Both models have nearly 800000 zones. The size of the mesh is 2−3 mm.

4.1.2 Simulation of formation process of core disicng during drilling

In order to view the forming process of core discing during drilling, this section simulates coring step by step, with the coring length increasing by 2.5 mm each time. FLAC^{3D} can simulate continuum materials, but it cannot simulate crack and fracture. However, the large plastic strain can identify the potential fracture. According to the model and parameters given in the Section 4.1.1, the plastic strain was monitored for the horizontal stress σ_h=62 MPa and vertical stress σ_v=124 MPa loading case and the normal rectangular crown drill bit with a flat bottom shape was used.

Figure 7 shows the tensile plastic strain of the middle section of the model with same scale in five typical drilling steps. The shear plastic strain was not included because there was no obvious such strain in the whole process and this will be showed in the later section. We can see that there was no tensile plastic strain at the first stage of coring when stub length r=2.5 mm (Figure 7(a)). As the removed zones increased, which represented the drilling went deeper, the tensile plastic strain began to appear in the middle of the core (Figure 7(b) r=10.0 mm). At this stage, the core had not broken because the tensile failure was not connected to the core surface. In Figure 7(c) (r=15.0 mm), the tensile plastic strain at the position of A reached 1.1%, which was 35 times higher than that at B (0.03%). We assumed that the core would crack along the "potential crack zone", which had larger tension plastic strain. Thus, the core broke and formed into a thin disc since the large tensile plastic strain was observed and expanded throughout the core. The failed zone can be assumed to be a new surface of the core, allowing for a redistribution of the tensile stress. As drilling processes, the tensile zone will eventually be rebuilt to restart the local tensile failure zone across the core. The above process was repeated, zones with large tensile plastic strain formed again in the center of the core as drilling went deeper, as shown in Figure 7(d) (r=27.5 mm).



(a) (b) (c) (d) (e)

Figure 7 Tensile plastic strain during drilling for σ_h=124 MPa, σ_v=62 MPa loading case: (a) Stub length r=2.5 mm; (b) r=10.0 mm; (c) r=15.0 mm; (d) r=27.5 mm; (e) r=37.5 mm

This area gradually penetrated to the core surface, creating potential crack zone and the core broke into another disc (Figure 7(d) *r*=37.5 mm).

The above simulation results were obtained when the horizontal stress was 124 MPa and the vertical stress was 62 MPa. Plastic tensile strain indicated tensile failure, so the core crack and propagation was caused by tensile stress. This was because the drilling process was stress relief for the core, so the core was subjected to tensile stress, as we mentioned in Figure 2. As the drilling process continued, the crack spread throughout the core and the core broke into a disc. This process was repeated throughout the drilling process and formed the phenomenon of core discing. Thus, at this stress level, core discing associated with tensile failure.

4.1.3 Core disicng with different drill bits under different stress combinations

In order to verify the proposed approach, the inner conical drill bit and rectangular crown drill bit were adopted for the simulation under different stress combinations. For simplification, the direction of the principal stress was assumed to be consistent with the coordinate axes. Five stress combinations were adopted to test the occurrence of core discing. The horizontal principal stresses were selected as 62 MPa, while the vertical principal stress were 140, 124, 108, 92 and 76 MPa, respectively.

Figure 8 details the plastic strain for these five stress combinations after coring 140 mm using two different drill bits which has different wear shape (rectangular and inner crown). Since the plastic strain had reflected the fracture, the differences in the plastic strain distribution at same stress level indicated that the different drill bits crowns had certain influences on the formation of cracks in the rock core, which may have eventually caused core discing.

Figure 8(a) shows both tension plastic strain and shear plastic strain for the σ_h=140 MPa, σ_v=62 MPa loading case. As we can see, the tensile fracture ran throughout the rock core and was regularly distributed along the *z* axis. The core was divided into seven regions, each representing a rock disc. However, the shear fracture only exited at the edge of the core, which was also conducive to the core failure. Under this stress condition, the disced cores were formed due to tensile failure or a combination of tensile and shear failure, and with both drill bits, discs were formed. Therefore, it could be seen that under the condition of higher in-situ stress, the inner conical crown drill bit is of no use to reduce core discing. With the decrease of the vertical stress σ_v, the shear stress on the core decreased, the shear plastic strain faded and the core fracture was dominated only by tensile failure. Therefore, the cloud diagram of shear plastic strain was no longer given in the following figure. In Figures 8(b) and 8(c), core discing all appeared. The tension plastic strain drilling with inner conical crown drill was greater than that of the rectangular crown drill bit in Figure 8(b). However, in Figure 8(c), the results turned out to be the opposite. The tensile fracture drilling with inner conical crown drill was slighter in the middle of the rock

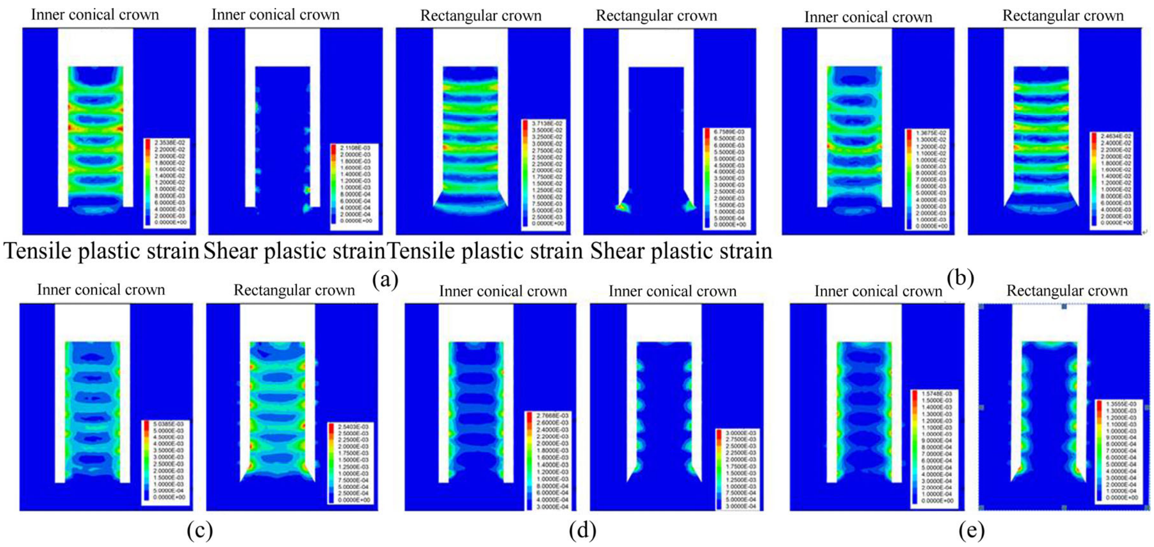


Figure 8 Plastic strain during drilling under different stress combinations: (a) σ_h=140 MPa, σ_v=62 MPa; (b) σ_h=124 MPa, σ_v=62 MPa; (c) σ_h=108 MPa, σ_v=62 MPa; (d) σ_h=92 MPa, σ_v=62 MPa; (e) σ_h=76 MPa, σ_v=62 MPa

core. This was also observed in Figures 8(d) and (e). When the inner conical crown drill bit was used, it only had tensile failure at the edge of the core and no disced cores were formed. However, under the same stress levels, when using the rectangular crown drill bit, the core would still form into discs. Thus, in these cases, the inner conical crown drill bit was effective in mitigating core discing.

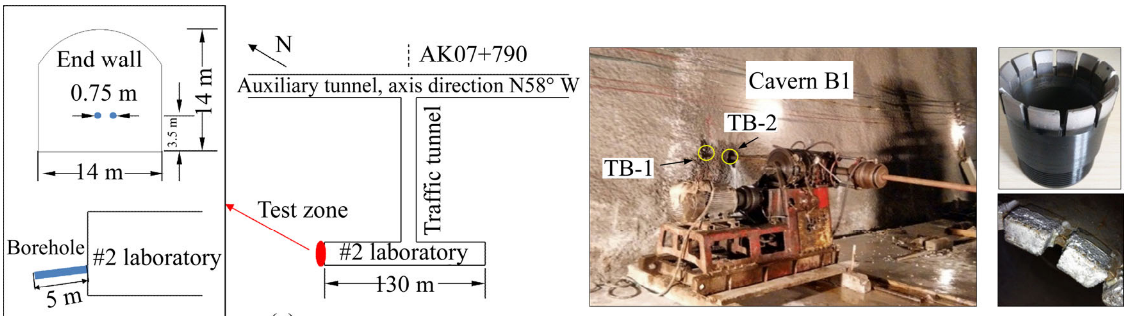
It is clear that core discing is not a binary phenomenon which is either present or absent. Core discing is one extreme manifestation of what could be called core damage which occurs when diamond drilling in rock that is weak relative to the in-situ stress field. In such cases, depending on the ratio between the different in-situ stresses, on the rock strength parameters in the core being drilled may initiate and propagate shear or tensile failure (or both). In some cases, when the right conditions are met, core discing or the separation of the core in various pieces will occur. The shape of the wear section would affect the release and evolution of stress and strain, and it had been found from the simulation results that the inner conical crown drill bit can reduce the plastic strain, thus mitigating core dising under certain stress conditions compared with the rectangular crown drill bit. However, the drill bit was no longer play a decisive role for core discing when the difference of the principle stresses was too large. In general, it had been determined through this study's simulations results that the reasonable selection of a drill bit crown during drilling could potentially be a new approach to avoiding or mitigating the occurrences of core dicing under certain stress conditions.

4.2 Validation by field testing

In order to verify the effectiveness of the proposed new approach of developing a reasonable drill bit crown, a field test was carried out in the cavern B1 of the China's Jinping Underground Laboratory Phase II (CJPL-II). The laboratory is located in the transitional slope zone between the Qinghai-Tibet Plateau and the Sichuan Basin. The lithology in the area is marble from the middle Triassic Baishan Formation (T2b). There are currently five scientific tunnels which can be divided into a total of ten caverns [17, 18], this study's field test site was located in the cavern B1 of the CJPL-Ⅱ, the cavern has the length of 130 m, and the geometric measurements of the arch sections are 14 m×14 m, as shown in Figure 9(a).

The inner conical crown impregnated diamond drill bit which was used in the testing was prepared using an artificial diamond and iron matrix and a hot-press sintering method. A vertical shaft coring drill rig was used to drill the test borehole (TB-1) in the end wall with an inner conical crown diamond drill bit, and the phenomenon of core discing was observed and statistically analyzed. At the same time, at a distance 75 cm from the TB-1, another test borehole (TB-2) was drilled with the same drilling equipment, with the exception that a rectangular crown diamond drill bit was used. The TB-1 borehole was drilled first, and then the TB-2 borehole was drilled, as shown in Figure 9(b). The core discing phenomena in the test boreholes which had been drilled using the different drill bits were compared for the purpose of verifying the effectiveness of each testing drill bit, as shown in Figure 9(c).

In the present study, two boxes of cores which had been drilled using the inner conical diamond drill bit and ordinary rectangular crown diamond drill bit were measured, as detailed in Figures 10(a) and (b). Then, simple sketch maps of the cores were drawn, respectively. During the experiment, due to



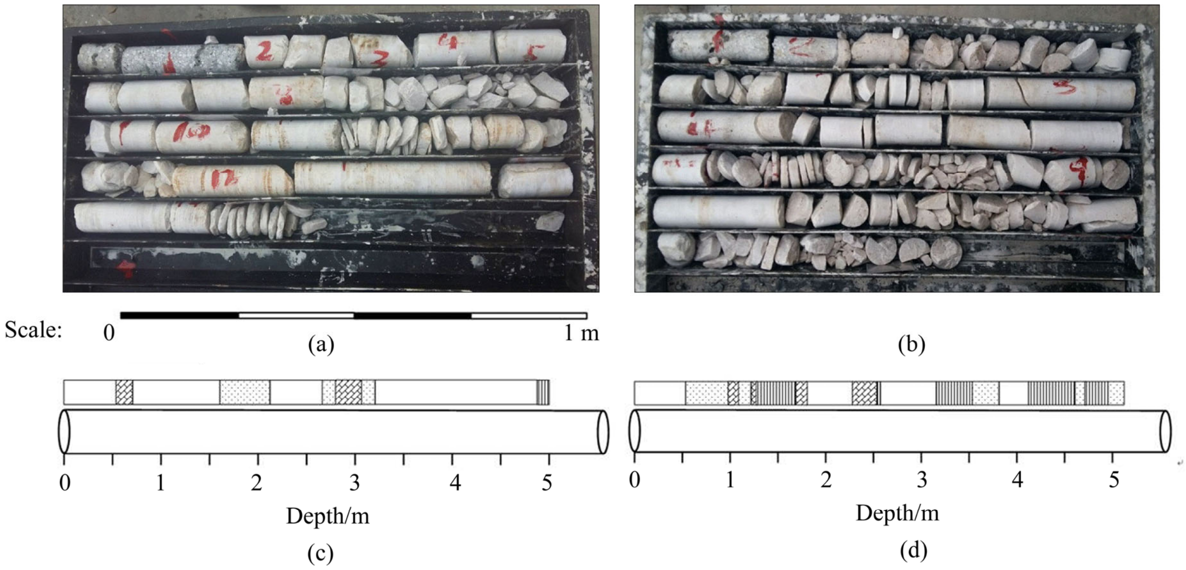
(a) (b) (c)

Figure 9 Overview of field tests: (a) Layout of borehole drilling sites; (b) Image of field test; (c) Drill bits with an inner conical crown (figure above) and a rectangular crown (figure below) field restrictions, the cores drilled by the diamond drill bits with rectangular and inner conical crowns were 5.21 m and 4.91 m long, respectively. The cores were divided into different zones, as shown in Figures 10(c) and (d), each representing one type of core discing. The results showed that core discing had existed in both cores. However, the core of the TB-1 borehole was found to have more intact zones than that of the TB-2 borehole. As shown in Table 3, the percentage of the discing zone of the TB-2 was 67.8%, which was more than 2.5 times that of the TB-1 (26.5%). In addition, the core at the discing zone drilled using the rectangular crown drill bit was observed to be seriously broken, as shown in Figure 10(b). As can be seen from field testing, although the length of the drill hole was limited, the core drilled with inner conical crown drill bit had less disced rock cores and is more integrated.

5 Discussion

In-situ stress is one of the most important factors contributing to rock engineering designs, and plays a major role in the deformations and fractures of underground rock engineering projects, such as mines, traffic tunnels, and hydropower stations [15, 27, 28]. However, it was observed that during the in-situ stress measurements processes using over-coring stress relief methods in the deep tunnels, the occurrence of core discing would lead to measurement failure, as shown in Figure 11. Therefore, effectively solving the problem of core discing during drilling has become an important content of in-situ stress measurement processes. The inner conical crown impregnated diamond drill bit was found to have effectively reduced the phenomena of core discing under certain stress conditions. Therefore, it could be utilized in future field tests as a new and convenient method by which to improve the in-situ stress measurements in deep rock. To illustrate this distinction further, Figure 12 shows the plastic strains of the rock core during the process of over-coring with both drill bits. As we can see, the core drilling with rectangular crown drill bit was cracked into serval discs (Figure 12(a)). These ring-like cores will lead to failure of over-coring stress relief tests because of the stress measurement probes cannot measure the data properly due to the core fracture. However, the core drilling with inner conical crown drill bit did not break into discs and maintained integrity during the measurement processes (Figure 12(b)).

Like all numerical simulations, the simulation used in this paper also made some simplifications and assumptions. Only limited stress combinations and the drill bit section were considered and the failure was identified by plastic strain. Despite these simplifications, numerical simulations can still provide insight into the problems in the paper as a convenient and economical method. Compared with the other numerical simulations of core dising, this paper focuses on the influence of different drill bit sections on the occurrence of core discing and persuade a new approach to mitigate core discing.



(a) (b) (c) (d)

Figure 10 Images of test boreholes and simple sketch maps of cores: (a) Rock cores from TB-1; (b) Rock cores from TB-2; (c) Sketch map of rock cores from TB-1; (d) Sketch map of rock cores from TB-2

Table 3 Length of different core zones and percent of core discing

Zone	Zone length/m	
	TB-1	TB-2
Intact rock mass	3.61	1.68
Thick discing	0.5	0.65
Medium discing	0.6	1.6
Crushed discing	0.2	1.28
Total length	4.91	5.21
Percent of core discing/%	26.5	67.8

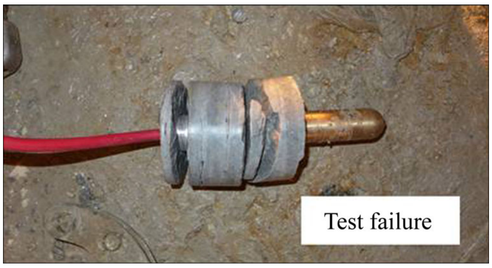


Figure 11 In-situ stress test failure due to core discing when using an over-coring stress relief method

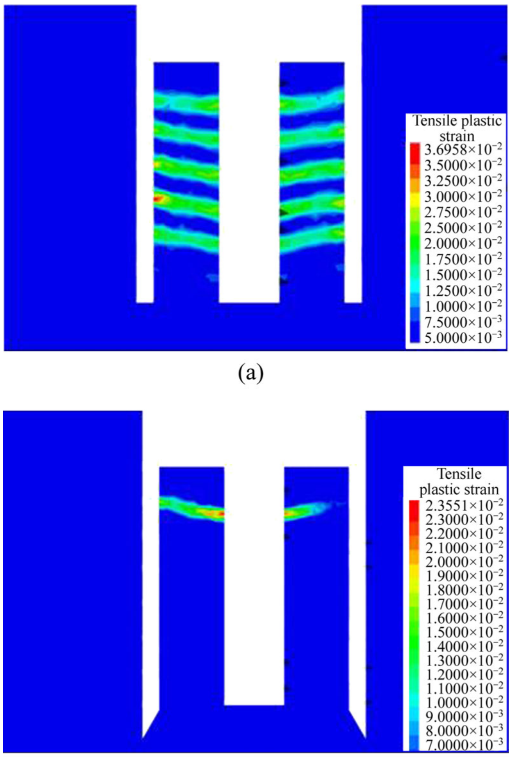


Figure 12 Tensile plastic strain during over-coring for σ_h=100 MPa, σ_v=62 MPa loading case: (a) Model drilled with rectangular crown drill bit; (b) Model drilled inner conical crown drill bit

The understanding of the mitigation of core disking is still in the preliminary stage and more experiments including laboratory tests, numerical simulations and field tests are needed to find more suitable and convenient approaches for practice.

6 Conclusions

The formation mechanism of core discing was investigated and the interaction mechanism between the rock and the drill bits during drilling was analyzed. A new approach for core discing mitigation was proposed and verified by numerical analysis and field tests, the following conclusions can be drawn:

1) Numerical analysis indicated that the shapes of the drill bit crowns will affect the stress and strain distributions of the rock when drilling activities are being conducted. Core discing mainly related to the tensile failure and it begins in the middle of the rock core while shear failure exits on the edge of the core. Under certain stress conditions, the inner conical crown drill bit can effectively avoid the occurrence of core disicng.

2) Field tests in the cavern B1 of CJPL-II laboratory demonstrated that the inner conical crown diamond drill bit was better than the rectangular crown drill bit in mitigating core discing. The percentage of core discing was observed to have been reduced from 67.8% when drilling with an ordinary rectangular crown drill bit, to 26.5% when drilling with an inner conical crown drill bit.

3) This study determined that the novel developed drill bit had proven effective in the mitigation of core discing. Therefore, it could be potentially utilized in future field tests as a convenient and inexpensive approach for improving the accuracy of in-situ stress measurements in deep rock.

Contributors

The general idea and method of this paper were developed by ZHENG Ming-zong and LI Shao-jun. ZHENG Min-zong was responsible for the full-text writing. YAO Zou and ZHANG Ao-dong provided drill bits and ZHOU Ji-fang provided a site for the field test in this paper. ZHENG Min-zong and XU Ding-ping carried out numerical simulation. LI Shao-jun and XU Ding-ping edited the draft of manuscript. All authors replied to reviewers' comments and revised the final version.

Conflict of interest

ZHENG Ming-zong, LI Shao-jun, YAO Zou, ZHANG Ao-dong, XU Ding-ping, and ZHOU Ji-fang declare that they have no conflict of interest.

References

[1] HAST N. The state of stress in the upper part of the earth's crust [J]. Tectonophysics, 1969, 2(1): 5−17. DOI: 10.1016/0013-7952(67)90002-6.

[2] JAEGER J C, COOK N G W. Pinching-off and disking of rocks [J]. Journal of Geophysical Research, 1963, 68(6): 1759−1765. DOI: 10.1029/JZ068i006p01759.

[3] ZHU Wei-shen, LI Guang-yu, WANG Ke-jun. Analyses of disking phenomenon and stress field in the region of an underground powerhouse [J]. Rock Mechanics and Rock Engineering, 1985, 18(1): 1−15. DOI: 10.1007/BF01020412.

[4] BELOV N I, IVANOV V I. Numerical modelling of the stressed state of the foot of a borehole with a study of drill core disking [J]. Journal of Mining Science, 1992, 28(6): 500−503. DOI: 10.1007/ BF00734064.

[5] WU S, WU H, KEMENY J. Three-dimensional discrete element method simulation of core disking [J]. Acta Geophysica, 2018, 66(3): 267−282. DOI: 10.1007/s11600-018-0136-z.

[6] CORTHÉSY R, LEITE M H. A strain-softening numerical model of core discing and damage [J]. International Journal of Rock Mechanics & Mining Sciences, 2008, 45(3): 329−350. DOI: 10.1016/j.ijrmms.2007.05.005.

[7] MATSUKI K, KAGA N, YOKOYAMA T, TSUDA N. Determination of three dimensional in situ stress from core discing based on analysis of principal tensile stress [J]. International Journal of Rock Mechanics & Mining Sciences, 2004, 41(7): 1167−1190. DOI: 10.1016/j.ijrmms.2004.05.002.

[8] LIM S S, MARTIN C D. Core disking and its relationship with stress magnitude for Lac du Bonnet granite [J]. International Journal of Rock Mechanics & Mining Sciences, 2010, 47(2): 254−264. DOI: 10.1016/j.ijrmms.2009.11.007.

[9] KANG S S, ISHIGURO Y, OBARA Y. Evaluation of core disking rock stress and tensile strength via the compact conical-ended borehole overcoring technique [J]. International Journal of Rock Mechanics & Mining Sciences, 2006, 43(8): 1226−1240. DOI: 10.1016/j.ijrmms.2006.04.007.

[10] FAIRHURST C. Stress estimation in rock: A brief history and review [J]. International Journal of Rock Mechanics & Mining Sciences, 2003, 40: 957−973. DOI: 10.1016/j.ijrmms.2003.07.002.

[11] LEITE M H, BOIVIN V, CORTHÉSY R. Stress calculation methods for overcoring techniques in heterogeneous rocks [J]. International Journal of Rock Mechanics and Mining Sciences, 2010, 47(7): 1180−1192. DOI: 10.1016/j.ijrmms.2010.06.002.

[12] OUYANG Zhen-hua, LI Chang-hong, XU Wan-cai, LI Hao-jie. Measurements of in situ stress and mining-induced stress in Beiminghe Iron Mine of China [J]. Journal of Central South University of Technology, 2009, 16(1): 85−90. DOI: 10.1007/s11771-009- 0014-6.

[13] ZHANG Feng-peng, QIU Zhao-guo, FENG Xia-ting. Non-complete relief method for measuring surface stresses in surrounding rocks [J]. Journal of Central South University, 2014, 21(9): 3665−3673. DOI: 10.1007/s11771-014-2349-x.

[14] LI Shao-jun, FENG Xia-ting, LI Zhan-hai, CHEN Bing-rui, ZHANG Chuan-qing, ZHOU Hui. In situ monitoring of rockburst nucleation and evolution in the deeply buried tunnels of Jinping II hydropower station [J]. Engineering. Geology, 2012, 137: 85−96. DOI: 10.1016/j.enggeo.2012.03.010.

[15] LI Shao-jun, FENG Xia-ting, LI Zhan-hai, ZHANG Chuan-qing, CHEN Bing-rui. Evolution of fractures in the excavation damaged zone of a deeply buried tunnel during TBM construction [J]. International Journal of Rock Mechanics & Mining Sciences, 2012, 55: 125−138. DOI: 10.1016/j.ijrmms.2012.07.004.

[16] LI Zhan-hai, LI Shao-jun, ZHOU Hui, CHEN Bing-rui, ZHANG Chuan-qing. Characteristics and formation mechanism of core discing in deep rock mass [J]. Chinese Journal of Rock Mechanics & Engineering. 2011, 30(11): 2254−2266. DOI: CNKI:SUN:YSLX.0.2011-11-012. (in Chinese)

[17] FENG Xia-ting, XU Hong, QIU Shi-li, LI Shao-jun, YANG Cheng-xiang, GUO Hao-sen, CHENG Yuan, GAO Yao-hui. In situ observation of rock spalling in the deep tunnels of the china jinping underground laboratory (2400 m depth) [J]. Rock Mechanics & Rock Engineering, 2018, 51: 1193−1213. DOI: 10.1007/s00603-017-1387-8.

[18] HU Lei, FENG Xia-ting, XIAO Ya-xun. Characteristics of the microseismicity resulting from the construction of a deeply-buried shaf [J]. Tunnelling and Underground Space Technology, 2019, 85: 114−127. DOI: 10.1016/j.tust.2018.12.016.

[19] LI Shu-sen, NIE De-xin, RE Guang-ming. The fracture mechanism of discal drill core and its influence on characteristic of engineering geology [J]. Advance in Earth Sciences. 2004, 19(S1): 384−387. http://www.cnki.com.cn/Article/CJFDTotal-DXJZ2004S1076.htm. (in Chinese)

[20] SHI Yu-peng, XIA Yi-min, TAN Qing, ZHANG Yi-chao, QIAO Shuo. Distribution of contact loads in crushed zone between tunnel boring machine disc cutter and rock [J]. Journal of Central South University, 2019, 26(9): 2393−2403. DOI: 10.1007/s11771-019-4182-8.

[21] WANG Jia-liang, ZHANG Shao-he. A new diamond bit for extra-hard, compact and nonabrasive rock formation [J]. Journal of Central South University, 2015, 22: 1456−1462. DOI: 10.1007/s11771-015-2663-y.

[22] JIANG An-nan, ZENG Zheng-wen, TANG Chun-an. Three-dimensional numerical test of element safety degree of rock core discing and feed-back analysis of geostresses [J]. Chinese Journal of Rock Mechanics & Engineering, 2010, 29(8): 1610−1617. DOI: CNKI:SUN:YSLX.0.2010-08-015. (in Chinese)

[23] ALEJANO L R, ALFONSO R D, MARÍA V. Plastic radii

and longitudinal deformation profiles of tunnels excavated in strain-softening rock masses [J]. Tunnelling and Underground Space Technology Incorporating Trenchless Technology Research, 2012, 30: 169−182. DOI: 10.1016/j.tust.2012.02.017.

[24] LEE Y K, PIETRUSZCZAK S. A new numerical procedure for elasto-plastic analysis of a circular opening excavated in a strain-softening rock mass [J]. Tunnelling and Underground Space Technology, 2008, 23(5): 588−599. DOI: 10.1016/j.tust.2007.11.002.

[25] SI Xue-feng, GONG Feng-qiang. Strength-weakening effect and shear-tension failure mode transformation mechanism of rockburst for fine-grained granite under triaxial unloading compression [J]. International Journal of Rock Mechanics & Mining Science, 2020, 131: 104347. DOI: 10.1016/j.ijrmms.2020.104347.

[26] ZHENG Zhi, FENG Xia-ting, ZHANG Xi-wei, ZHAO Jun, YANG Cheng-xiang. Residual strength characteristics of CJPL marble under true triaxial compression [J]. Rock Mechanics and Rock Engineering, 2019, 52: 1247−1256. DOI: 10.1007/s00603- 018-1659-y.

[27] MARTINO J B, CHANDLER N A. Excavation-induced damage studies at the underground research laboratory [J]. International Journal of Rock Mechanics & Mining Sciences, 2004, 41(8): 1413−1426. DOI: 10.1016/j.ijrmms.2004.09.010.

[28] YAN Fei, PAN Peng-zhi, FENG Xia-ting, LI Shao-jun. The continuous-discontinuous cellular automaton method for elastodynamics crack problems [J]. Engineering Fracture Mechanics, 2018, 204: 482−496. DOI: 10.1016/j.engfracmech.2018.10.025.

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中文导读

深部岩石岩芯饼化特征及减轻岩芯饼化的新型钻头设计

摘要：岩芯饼化是深部岩石在高应力条件下钻孔时经常发生的现象，是深部岩石工程的一个重要特征。本文首先介绍了岩芯饼化的形成机理，基于数值模拟分析了金刚石钻头与岩石之间的相互作用，通过数值模拟实验设计并验证了一种可以用于减轻岩芯饼化的新型内圆锥形冠状金刚石钻头。将该方法应用于 CJPL-Ⅱ的 B1 实验室中，取得了满意的效果，饼化岩芯所占的百分比从使用矩形冠状钻头钻进时的 67.8%明显降低到采用内圆锥形冠状钻头时的 26.5%。本文全面介绍了深部岩石岩芯饼化特征，并为缓解岩芯饼化现象提供了一种新方法，这将有助于深部岩石工程中的应力测量。

关键词：岩芯饼化；缓解；钻头冠部；深部岩石；原岩应力测量