STUDY ON MECHANICAL BEHAVIOR AND MICROSCOPIC FAILURE CHARACTERISTICS OF DEEP ROCKS CONSIDERING THE INFLUENCE OF INTERNAL STRESS

by

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Original scientific paper
https://doi.org/10.2298/TSCI2502295L

To address the limitation of traditional discrete element modelling in considering internal stress, this study proposes a new numerical simulation process based on particle flow code in 2-D, which successfully achieves internal stress consolidation-sealing. Triaxial compression tests were conducted to analyze the impact of internal stress evolution on rock mechanical properties. Under a confining pressure of 10-20 MPa, internal stress causes the peak stress of the rock to be higher than when there is no internal stress, while the opposite is true at 30-40 MPa. The elastic modulus is consistently higher in rocks with internal stress. The trend of increasing the number of rock cracks with and without internal stress is similar, and the growth rate of tensile cracks is higher than that of shear cracks. Internal stress promotes crack propagation. The axial development of cracks is more pronounced. This study offers new insights into in-situ rock mechanics.

Key words: *in-situ rock mechanics, internal stress consolidation-sealing, discrete element method, new numerical simulation process*

Introduction

Energy resources are fundamental to the development of the national economy and technological advancement [1-3]. As shallow energy resources become depleted, exploiting the abundant deep energy resources has become a necessary measure [4-6]. However, deep mining encounters significant challenges due to frequent high intensity disasters, such as rock bursts and coal bumps, caused by the complex mechanical properties of deep rock masses under high stress conditions [7, 8]. Currently, the theories and technologies for disaster prevention and control are insufficient to meet engineering demands, primarily due to the neglect of the influence of internal stress on rock mechanics. Although internal stress has been acknowledged by many scholars and aids in explaining phenomena such as rock burst and core discing [9, 10]. However, the occurrence of these phenomena clearly changes the in-situ structural characteristics of rocks. This discrepancy leads to measured parameters that do not align with reality, thereby affecting the application of theoretical models in engineering. Consequently, to safely

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and efficiently develop deep earth energy resources, it is imperative to investigate the in-situ mechanical behavior of deep rock masses under internal stress.

The discrete element method (DEM), introduced by Cundall and Strack, offers the advantage of intuitively tracking the rock fracture process and is extensively utilized in rock mechanics research [11]. Wang *et al.* [12] employed particle flow code (PFC) to simulate the coring process, discovering that drilling fluid pressure exerts an inhibitory effect on core splitting, although this influence is non-linear. Sinha *et al.* [13] compared the local and combined damping modes in universal distinct element code, finding that the results were similar in small-scale simulations but differed significantly in field-scale simulations. Jimenez-Herrera *et al.* [14] conducted copper ore impact breakage experiments using three particle breakage models and recommended improvements to these models to enhance accuracy and efficiency. Nevertheless, these studies did not account for the influence of internal stress. Therefore, it is imperative to incorporate internal stress into existing numerical simulations to investigate their impact on the mechanical properties of rock.

This study employed an innovative discrete element numerical simulation process using PFC in 2-D (PFC2D) to achieve internal stress consolidation-sealing. Subsequent triaxial compression tests were conducted both with and without internal stress. The differences in rock mechanical properties under these conditions were analyzed from the perspectives of stress-strain relationship and crack evolution characteristics. This analysis elucidates the influence mechanism of internal stress on rock deformation and failure processes, providing valuable insights for deep in-situ rock mechanics research.

Methodology

Using PFC2D to simulate the loading processes of rocks with and without internal stress, this study explores the influence of internal stress on the mechanical behavior of rocks. The macroscopic parameters of the model were derived from uniaxial compression tests conducted on rocks at a depth of 4900 m in Well Songke-2, exhibiting a uniaxial compressive strength (UCS) of 100.97 MPa and an elastic modulus, E, of 30.26 GPa [15, 16]. The model was constructed based on actual experimental dimensions (length of 20 mm and height of 40 mm), and the microscopic parameters using the parallel bond model (PBM) were calibrated through a trial and error method, as shown in fig 1. The calibrated numerical model achieved a UCS of 100.90 MPa (error of 0.07%), and an E of 29.99 GPa (error of 0.89%). The specific microscopic parameters are detailed in tab. 1.

Table 1. Microscopic parameters of PFC2D calculation model

Minimum particle radius [mm]	Maximum particle radius [mm]	Elastic modulus [GPa]	Particle stiffness ratio [–]	Particle friction coefficient [–]	Parallel bond elastic modulus [GPa]	Parallel bond stiffness ratio [–]	Parallel bond tensile strength [MPa]	Parallel bond cohesion [MPa]	Parallel bond friction angle [°]	Particle density [kgm^{-3}]
0.3	0.498	14.9	1.5	0.577	14.9	1.5	50	33.33	30	2625.9

The principles of DEM numerical simulation and the PBM have been comprehensively detailed in multiple studies and will not be reiterated in this study [17]. Instead, this study briefly introduces the new numerical simulation process proposed and utilized. A numerical model of a rock with dimensions of 50 mm in length and 100 mm in height was established using calibrated microscopic parameters. Following preloading, the target confining pressure, σ_3, was directly applied. The PBM was then applied between particles to achieve internal stress

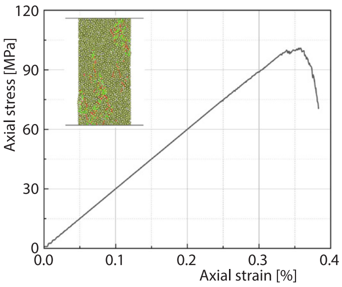

Figure 1. Calibration results of uniaxial compression test based on PFC2D

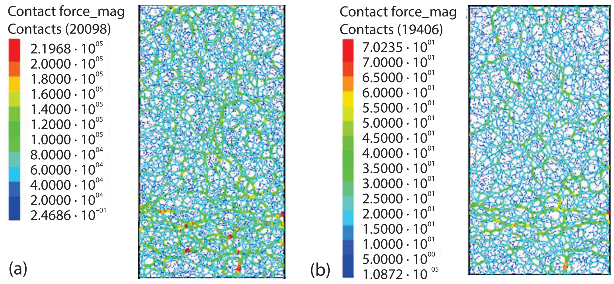

Figure 2. Distribution characteristics of contact force between particles following PBM application under different numerical simulation processes; (a) new numerical simulation process and (b) traditional numerical simulation process

consolidation-sealing. As shown in fig. 2(a), with a σ_3 of 40 MPa as an example, the contact force of particles under the new process reaches 0.22 MPa, compared to only 70.24 Pa in the traditional numerical simulation process, as shown in fig. 2(b). Finally, triaxial compression tests were conducted on rock numerical models with and without internal stress to obtain data on stress, strain, cracks, and other relevant factors.

Simulation results and analysis

Stress-strain relationship

As shown in fig. 3, the stress-strain curves, both with and without internal stress, exhibit a similar trend of initially increasing and subsequently decreasing. Higher σ_3 results in greater stress values corresponding to the same strain, thereby elevating the position of the curve. This phenomenon can be attributed to the fact that σ_3 constrains rock fracture and enhances its bearing capacity. Consequently, deformation decreases with increasing σ_3 under identical stress conditions, delaying the occurrence of rock peak failure.

The E and peak stress, σ_c, represent the resistance to elastic deformation and maximum bearing capacity of rocks, respectively [18, 19]. Analyzing these parameters elucidates the intrinsic relationship between mechanical characteristics and internal stress. As shown in fig. 4, when the σ_3 ranges from 10-40 MPa, both E and σ_c of the rock exhibit an increasing trend. However, the correlation between these parameters and internal stress varies. Regardless of the σ_3 within the 10-40 MPa range, the E of rocks with internal stress consistently exceeds that of rocks without internal stress. Within a σ_3 range of 10-20 MPa, rocks with internal stress demonstrate higher σ_c compared to those without internal stress. Conversely, within the 30-40 MPa range, the trend is reversed. This consistent difference may be attributed to internal stress enhancing the contact between rock particles, thereby improving their ability to undergo elastic deformation. However, excessive internal stress under high σ_3 may facilitate the development of cracks within the rocks, leading to premature peak failure.

Crack characteristics

Cracks are intimately associated with the mechanical properties of rocks and serve as a critical indicator of deformation and failure behavior [20, 21]. To facilitate the comparison of the differential effects of internal stress and σ_3 on crack evolution during loading, the ratio of axial stress to peak stress is used as the relative stress level, with σ_c serving as the reference

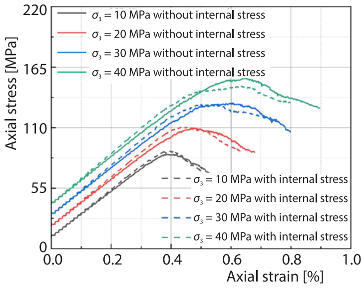

Figure 3. Changes in stress-strain curve with and without internal stress

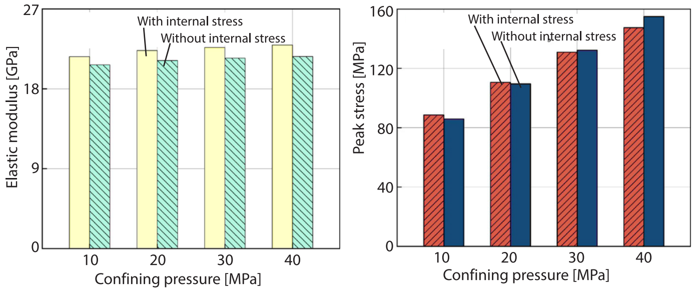

Figure 4. Comparison of mechanical parameters with and without internal stress; (a) elastic modulus and (b) peak stress

point. Figure 5 shows the changes in the number of cracks in the rock numerical model, both with and without internal stress. As shown in fig. 5, the number of cracks does not increase significantly in the initial stages of loading but begins to rise markedly as peak failure approaches. Notably, tensile cracks exhibit a much higher growth rate compared to shear cracks. Additionally, an increase in σ_3 results in a substantial rise in the number of cracks. Internal stress plays a significant role in promoting crack development, leading to a more rapid increase in the number of cracks in rocks with internal stress as they near peak failure, ultimately surpassing the crack count observed in rocks without internal stress.

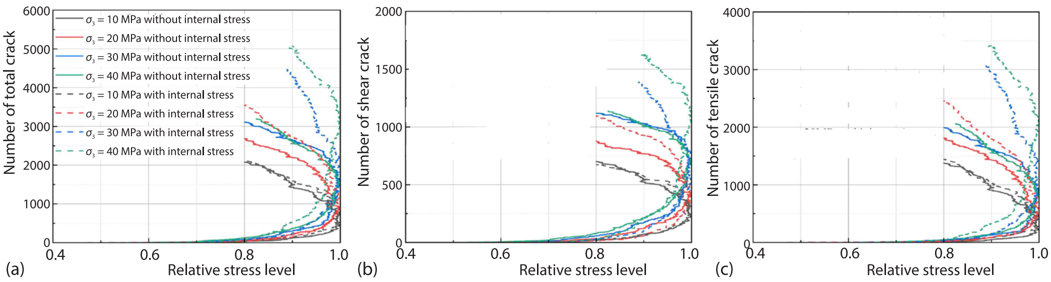

Figure 5. Changes in the number of cracks in the rock numerical model with and without internal stress during the loading process; (a) total crack, (b) shear crack, and (c) tensile crack

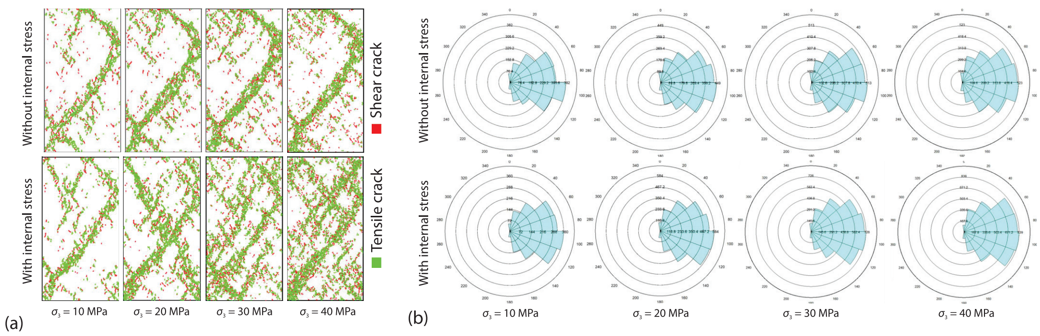

Figure 6. Comparison of crack distribution characteristics with and without internal stress; (a) spatial distribution pattern and (b) rose diagram of crack direction

Figure 6 shows a comparison of the differences in crack distribution characteristics between conditions with and without internal stress. As shown in fig. 6(a), the spatial distribution pattern of fractures is closely influenced by internal stress. In rocks without internal stress, there is a presence of one larger fracture surface and two smaller fracture surfaces. In contrast, rocks with internal stress exhibit not only a larger fracture surface but also a greater number of smaller fracture surfaces. This phenomenon occurs because internal stress promotes crack propagation, leading to more widespread damage within the rock structure. Figure 6(b) shows that although the orientation of cracks varies depending on the presence or absence of internal stress, the overall pattern remains consistent, that is, the closer the fracture direction is to the axial direction, the more fractures there are, indicating that the axial direction is the main direction of fracture development.

Conclusion

By conducting triaxial compression tests on numerical models of deep rocks with and without internal stress, the differences in mechanical properties and mesoscopic failure characteristics were studied. By adjusting the discrete element numerical simulation process, successful internal stress consolidation-sealing were achieved. When σ_3 reached 40 MPa, the maximum contact force of particles under the new process reached 0.22 MPa, compared to only 70.24 Pa under the traditional process. Within σ_3 range of 10-40 MPa, E and σ_c of rocks exhibit an increasing trend regardless of the presence of internal stress. However, the influence of internal stress on these parameters is not consistent. The growth trend of rock cracks, whether with or without internal stress, is similar. Increasing σ_3 significantly increases the number of cracks, while internal stress significantly promotes crack development. The spatial distribution of cracks is closely related to internal stress. The axial direction is the dominant direction for crack development.

Acknowledgment

This work was financially supported by the National Natural Science Foundation of China (52225403, U2013603) and National Key Research and Development Program of China (2023YFF0615401).

Nomenclature

E – elastic modulus, [GPa]

Greek symbols

σ_3 – confining pressure, [MPa]
σ_c – peak stress, [MPa]

Acronym

DEM – discrete element method
PFC – particle flow code
PFC2D – particle flow code in 2-D
PBM – parallel bond model
UCS – uniaxial compressive strength

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Paper submitted: August 15, 2024
Paper revised: November 03, 2024
Paper accepted: November 22, 2024