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Perspective

Research progress and prospect in nonlinear mechanical behavior and response of deep rocks

Beichen Yu[1,2], Chao Wang[3]*, Qiangui Zhang[4], Jiaxin Wang[3], Yubing Liu[1,2]*

[1] *Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology, Xuzhou 221116, P. R. China*

[2] *State Key Laboratory of Coal Mine Disaster Prevention and Control, China University of Mining and Technology, Xuzhou 221116, P. R. China*

[3] *Faculty of Land Resources Engineering, Kunming University of Science and Technology, Kunming 650031, P. R. China*

[4] *Petroleum Engineering School, Southwest Petroleum University, Chengdu 610500, P. R. China*

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Abstract:
The nonlinear mechanical behavior and response of deep rocks is essential for disaster mechanism revelation and accurate stability prediction. This study summarizes the principal outcomes from Session 50 of the second "International Geo-Energy Frontier Forum", entitled "Nonlinear Mechanical Behavior and Response of Deep Rocks." A total of 16 experts and scholars presented at the session, which covered a broad spectrum of topics in deep rock mechanics. Centering on the rock mechanics challenges in deep energy resource development and underground space utilization, this session synthesized research advances in anisotropic mechanical behavior, fatigue damage evolution, nonlinear strength criteria, and fracture mechanisms coupled with hydraulic synergistic control, and then outlined future research directions for deep rock mechanics. The perspectives presented were intended to provide theoretical and technical support for the safe and efficient development of deep earth resources.

1. Introduction

Advancing into the deep earth is a strategic imperative for safeguarding national energy security and achieving the carbon neutrality and carbon peak goals. As extraction depths increase progressively, deep rock masses reside in environments characterized by high in-situ stress, intense mining-induced disturbance, and multi-physics field coupling, with their mechanical response exhibiting pronounced nonlinearity, anisotropy, and time-dependent damage evolution. A thorough investigation into the nonlinear mechanical behavior and multi-field coupling response of deep rocks can help transcend the theoretical limitations rooted in the assumption of homogeneity and continuity, reveal multi-field coupling disaster mechanisms, and enable accurate prediction of deep rock mass stability.

The second "International Geo-Energy Frontier Forum", themed "New Opportunities and Challenges in Geo-Energy Exploration and Development", was successfully held in Zhengzhou, China. The forum featured 80 sessions spanning 70 topics, aimed at deepening fundamental theoretical innovation and key technological breakthroughs in the field of geo-energy (Cai, 2026). This work summarizes the principal outcomes of Session 50, "Nonlinear Mechanical Behavior and Response of Deep Rocks", and discusses the latest research advances and distills recent insights across four critical dimensions: multi-field coupling mechanisms anisotropy and the basis for stability assessment, energy criteria for fatigue damage under dynamic disturbance and precursor identification, intelligent modification of nonlinear strength criteria and

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*Corresponding author.
E-mail address: yubc@cumt.edu.cn (B. Yu); wangchao@kust.edu.cn (C. Wang); qgzhang@swpu.edu.cn (Q. Zhang); wangjiaxin2727@163.com (J. Wang); liuyubing@cumt.edu.cn (Y. Liu).

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the formulation of damage constitutive models, and mining-induced fracture mechanisms of surrounding rock coupled with hydraulic synergistic prevention and control technologies. The aim is to explore the core scientific issues underlying the nonlinear mechanical behavior of deep rocks and to provide both theoretical and technical support for the safe and efficient development of deep earth resources.

2. Anisotropic mechanical behavior and multi-field coupling response

Deep rocks exhibit pronounced anisotropic mechanical behavior and permeability characteristics in complex geological environments. In particular, under true triaxial coupled static-dynamic loading, the directional dependence of mechanical parameters and permeability of coal and rock masses is critical for engineering safety assessment (Liu et al., 2023). Classification indices for coal-rock burst proneness are also affected by anisotropic effects, giving rise to discrepancies, which necessitates establishing direction-sensitive classification criteria based on mechanistic understanding (Li et al., 2023). Concurrently, the anisotropic distribution of the effective stress coefficient is key to accurately predicting the deformation and stability of deep rock masses, as well as fluid migration (Yu et al., 2023). The asymmetric large deformation and zonal disintegration phenomena observed in deep surrounding rock have repeatedly warned that neglecting anisotropic multi-field coupling will lead to misjudgment of rock mass stability (Zhang et al., 2025). The anisotropic mechanical properties and multi-field coupling response of deep rocks constitute the core foundation for assessing engineering rock mass stability. Future research should integrate stress fields, seepage fields, and the orientation of rock structural planes in a coupled analysis to reveal the controlling mechanisms of anisotropy on the overall bearing capacity and long-term stability of rock masses.

3. Fatigue damage evolution by dynamic disturbance and cyclic loading

Dynamic stress fields and periodic loading exert a profound influence on the long-term behavior of deep rocks. Under impact and cyclic loading, the fatigue behavior and energy evolution of typical reservoir rocks such as sandstone exhibit a complex pattern in which phased accumulation coexists with sudden release (Chen et al., 2026); the critical transition from stable microcrack accumulation to accelerated growth and abrupt release depends on an energy density threshold that has yet to be clearly quantified. The rheological constitutive relations of rocks must also fully account for the time-dependent damage and energy dissipation processes triggered by dynamic disturbance (Chen et al., 2025). At the monitoring level, microcracking signals in anisotropic rocks are easily overwhelmed by environmental noise. Developing acoustic emission waveform and directional denoising and interpretation techniques makes it possible to extract the true spectral signatures of damage evolution from strong background interference (Wang et al., 2024a). More precise energy criteria are needed for the fatigue damage evolution of rocks induced by dynamic disturbance and cyclic loading. Subsequent research should focus on developing methods for identifying catastrophic failure precursors based on an energy dissipation threshold, thereby providing a quantitative basis for evaluating the long-term safety of deep rock masses under blasting and mining-induced disturbance.

4. Nonlinear strength criteria and damage constitutive models

Conventional rock strength theories exhibit significant limitations under deep high-stress and strong-disturbance conditions. Focusing on the mechanical behavior of deep dolomite, fractured rock, and cleat coal-rock, the development of a modified three-dimensional Hoek-Brown criterion and elastoplastic damage constitutive models has markedly improved the accuracy in describing nonlinear yielding and post-peak softening characteristics (Zhang et al., 2023). For strength parameter calibration, the combined use of discrete element numerical experiments and intelligent algorithms for inversion and construction has become an effective means of addressing the heterogeneity and nonlinear response of deep rocks (Wang et al., 2024b). It is worth noting that the thermal cracking effect induced by temperature fields accelerates the nucleation and propagation of microcracks among mineral grains, leading to a drastic deterioration of mechanical parameters (Pan et al., 2025); therefore, design parameters for deep geothermal development and nuclear waste disposal must carefully account for thermo-mechanical coupling damage. The intelligent modification of nonlinear strength criteria and the development of damage constitutive models provide theoretical support for deep rock mass computation (Shi et al., 2023). Accordingly, advancing the modification of strength criteria and the construction of constitutive models driven by physics and intelligence approach is a critical step toward ensuring accurate calculation of rock mass response in complex deep environments.

5. Mining-induced fracture mechanisms and hydro-mechanical synergistic control

The fluidization mining of deep coal requires the in-situ conversion of coal mass into transportable coal particle flows. Relevant scholars studied the fine fragmentation mechanism of bottom-slot coal cutting and the active transport and discharge technology of borehole hydraulic cavitation (Yuan et al., 2025), and also explored the feasibility of integrated regulation combining water-jet coal breaking and cavity creation with hydraulic transport of coal particles (Wen et al., 2025), offering a new approach to enhancing the permeability of deep low-permeability coal seams and improving coal particle transport capacity. Meanwhile, under deep excavation-induced disturbance, the evolution of water inrush in fault fracture zones exhibits strongly nonlinear and catastrophic characteristics, necessitating a deeper understanding of the mechanical mechanisms governing sudden permeability changes in fractured rock masses (Wang et al., 2026). Dynamic loading failure experiments on rock-coal composite samples further demonstrate that the interface fracture patterns and energy transfer pathways under different burst-proneness combinations significantly control the overall instability cascade reactions. The fracture mechanisms of mining-induced surrounding rock and hydro-mechanical synergistic prevention and control technologies are pivotal for achieving safe and efficient extraction of deep resources. Based on this, developing fusion prediction techniques that integrate directional filtering of microcracking signals under acoustic emission denoising with permeability mutation precursor parameters, and coupling them with active hydraulic control strategies, represents a crucial developmental direction for achieving synergistic governance of deep energy and resource engineering development and disaster control.

6. Conclusions

This work systematically elucidates the research advances and pressing challenges concerning the nonlinear mechanical behavior and response of deep rocks. Deep rock mechanics must integrate the effective stress principle and develop anisotropic multi-field theory to evaluate the stability of deep rock masses. Fatigue failure induced by dynamic disturbance urgently requires the integration of acoustic emission directional denoising and interpretation to achieve early warning of delayed instability in the absence of significant displacement precursors. Strength criteria driven by physics and intelligence approach can effectively characterize nonlinear hardening-softening behavior and parameter degradation under high stress and high temperature fields. Deep fluidization mining and water inrush prevention constitute the two poles of solid resource extraction efficiency and safety. Future deep rock mechanics must advance along the main line of research encompassing unified anisotropic multi-field theory, quantification of energy catastrophe thresholds, intelligent precursor fusion and early warning, and synergistic regulation, thereby building a technological system of deep earth scientific exploration and engineering safety.

Conflict of interest

The authors declare no competing interest.

References

Cai, J. Forging the future of geo-energy: The one-journal-one-forum mode and the path to global excellence. Advances in Geo-Energy Research, 2026, 20(1): 98-100.

Chen, J., Shen, X., Zhou, L., et al. The mechanical behaviors of sandstones in response to true triaxial graded perturbations of the intermediate principal stress. Fatigue and Fracture of Engineering Materials and Structures, 2026, 49(2): 574-594.

Chen, Y., Zhao, G., Xu, W., et al. Development and application of rock rheological constitutive model considering dynamic stress field and seepage field. International Journal of Mining Science and Technology, 2025, 35(3): 467-482.

Li, Y., Wang, C., Liu, Y. Classification of coal bursting liability based on support vector machine and imbalanced sample set. Minerals, 2023, 13(1): 15.

Liu, Y., Wang, E., Jiang, C., et al. True triaxial experimental study of anisotropic mechanical behavior and permeability evolution of initially fractured coal. Natural Resources Research, 2023, 32(2): 567-585.

Pan, Y., Zhang, Y., Gao, M., et al. Experimental study on the mechanical properties and acoustic emission characteristics of hot dry granite under thermo-mechanical coupling conditions. Geothermics, 2025, 132: 103435.

Shi, H., Chen, W., Zhang, H., et al. Dynamic strength characteristics of fractured rock mass. Engineering Fracture Mechanics, 2023, 292: 109678.

Wang, C., Zhang, D., Xiong, Z., et al. Acoustic emission noise reduction: a case of a uniaxial compression test of gypsum-like rock. International Journal of Rock Mechanics and Mining Sciences, 2024a, 178: 105781.

Wang, C., Zhang, D., Zhong, W., et al. Precursor response mechanism of tunnel water surge in water-rich fault fracture zones based on similar physical model. Tunnelling and Underground Space Technology, 2026, 170: 107403.

Wang, J., Wu, S., Cheng, H., et al. A generalized nonlinear three-dimensional Hoek-Brown failure criterion. Journal of Rock Mechanics and Geotechnical Engineering, 2024b, 16(8): 3149-3164.

Wen, X., Yin, L., Liu, Y., et al. CFD-DEM investigation of vortex characteristics within the hydraulic jet pumps in the vertical hydraulic conveying process. Chemical Engineering Journal, 2025, 507: 159576.

Yu, B., Zhang, D., Li, S., et al. Biot's coefficient and permeability evolution of damaged anisotropic coal subjected to true triaxial stress. Rock Mechanics and Rock Engineering, 2023, 56(1): 237-260.

Yuan, M., Sun, S., Liu, Y., et al. Modeling and control method of coal instability around cavity under water jet impact loading. Tunnelling and Underground Space Technology, 2025, 161: 106574.

Zhang, Q., Yao, B., Fan, X., et al. A failure criterion for shale considering the anisotropy and hydration based on the shear slide failure model. International Journal of Mining Science and Technology, 2023, 33(4): 447-462.

Zhang, T., Zheng, X., Wang, S., et al. Discrimination, mechanical mechanisms, and control technologies for large deformation in tunnel surrounding rock: A state-of-the-art review. Tunnelling and Underground Space Technology, 2025, 163: 106712.