energies

Editorial

Advances in Multifield and Multiscale Coupling of Rock Engineering

Chun Zhu [1,2,3,*], Jiabing Zhang [2,4], Junlong Shang [5], Dazhong Ren [1] and Manchao He [2,4]

1 Shaanxi Key Laboratory of Advanced Stimulation Technology for Oil & Gas Reservoirs, College of Petroleum Engineering, Xi'an Shiyou University, Xi'an 710065, China; dzren@xsyu.edu.cn
2 School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China; manchaohecumtb@163.com (M.H.)
3 State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan 232001, China
4 State Key Laboratory for Geomechanics & Deep Underground Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China
5 James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK; junlong.shang@glasgow.ac.uk
* Correspondence: zhu.chun@hhu.edu.cn

1. Introduction

In deep rock engineering, the stability of the rock is a key factor. Rocks are composed of different internal structures at different scales. Both microstructures (such as minerals, porosity, and fractures) and the geological environment (such as geostress and being underground) lead to an explosive complex coupling system. Multifield and multiscale coupling modeling provides a very powerful framework to understand the behavior of rocks in natural and engineered states, incorporating theoretical, numerical, and experimental analysis.

The past few years have witnessed the advances and applications of multifield and multiscale coupling in rock mechanics and rock engineering. Multifield addresses the interaction of different physical behaviors, such as in pores, fractures, and fluids. Multiscale refers to the scale of rock mechanics and engineering and may range from the nano-scale to the meter scale for material characterization purposes, and to hundreds of kilometers for geological applications.

This Special Issue aims to provide a platform for publishing original articles and reviews on recent numerical and experimental advances and applications on multiscale and multi-physics couplings in rock mechanics and engineering. Since the launch of the Special Issue, a total of 30 well-known scholars have submitted their research work to this Special Issue. Following strict quality screening, thirteen high-level papers have been published in the *Energies* journal, and the acceptance rate is 43%.

2. Special Issue Content

Gao et al. [1] calculated and examined the stability of perilous rock masses on the surface of the coal mine before and after mining, and the movement law of the overlying strata in the goaf, the movement and deformation law, and the failure mode of perilous rock were analyzed. This study provides a theoretical basis for the treatment of unstable rock and coal seam mining, and has important guiding significance for safe and efficient production within the mine. The results demonstrate the following: (1) The perilous rock is basically in a stable state without the influence of mining. Through theoretical analysis and the construction of the collapse model of perilous rock, it was judged that perilous rocks W1, W3, W4, and W7 were basically stable, perilous rocks W2 and W5 were in an unstable state, and perilous rock W6 was stable without heavy rainfall. (2) As a result of the mining of the C3 coal seam, the cracks in the upper strata begin to develop and rise to

Citation: Zhu, C.; Zhang, J.; Shang, J.; Ren, D.; He, M. Advances in Multifield and Multiscale Coupling of Rock Engineering. *Energies* **2023**, *16*, 4004. https://doi.org/10.3390/en16104004

Received: 4 May 2023
Accepted: 6 May 2023
Published: 10 May 2023

the surface, and the longitudinal separation cracks gradually appear between the surface perilous rock and the rock matrix. Due to the existence of these cracks, the perilous rock had a downward shear force. In addition, due to the heavy rainfall in the Guizhou area, the transient saturated zone of perilous rock expanded and the strength of perilous rock was reduced. The seepage increases the sliding force of the perilous rock and aggravates the opening of cracks at any time. (3) The stability of the surface perilous rock mass is largely affected by the mining of underground coal mines. The simulation analysis was repeated using the method of setting coal pillars. When 45 m permanent protection coal pillars are set at both ends, and 15 m local protection coal pillars are set at 60 m, the safety of coal mining can be ensured without affecting the surface and perilous rock.

Gao et al. [2] performed triaxial tests under cyclic multi-level loading at different rates using an MTS-815 Rock Mechanics Testing System. The strain characteristics, elastic modulus, and energy evolution were obtained in order to explore the effects of the mechanism of loading rate on the evolution of deformation and energy parameters of tectonic coal. The results showed that the irreversible strain and plastic energy increased exponentially with the increase in the deviatoric stress, but the growth rate decreased with the increase in loading rate. Furthermore, the elastic strain increased linearly and the growth rate was essentially unaffected by the loading rate. During the compaction stage, the variation in each parameter was not sensitive to the loading rate; during the elastic and damage stage, the rate increase inhibited secondary defect propagation and improved rock strength. In addition, the stepwise and cumulative energy ratio was defined in order to describe the energy distribution during cyclic loading and unloading. It was found that the decrease in the loading rate was beneficial to the transformation of the total energy into plastic energy. The elastic modulus was the most sensitive to sample damage, but the energy density evolution could be used to describe the deformation damage process of tectonic coal in more detail. These findings provide important theoretical support for the tectonic coal deformation law and action mechanism in the damage process that occurs under complex stress conditions.

Santos et al. [3] studied the wave anelasticity (attenuation and velocity dispersion) of a periodic set of three flat porous layers saturated by two immiscible fluids. The fluids are very dissimilar in regard to properties, namely gas, oil, and water, and, at most, three layers are required to study the problem from a general point of view. The sequence behaves as viscoelastic and transversely isotropic (VTI) at wavelengths much longer than the spatial period. Wave propagation causes fluid flow and slow P modes, inducing anelasticity. The fluids are characterized by capillary forces and relative permeabilities, which allow for the existence of two slow modes and the presence of dissipation, respectively. The methodology to study the physics is based on a finite-element upscaling approach to compute the complex and frequency-dependent stiffnesses of the effective VTI medium. The results of the experiments indicate that there is higher dissipation and anisotropy compared to the widely used model based on an effective fluid that ignores the effects of surface tension (capillarity) and viscous flow interference between the two fluid phases.

Hu et al. [4] carried out uniaxial compression tests on granite specimens damaged by cyclic loading using the digital speckle correlation method, so as to reveal the strength characteristics and crack damage fracture laws after rock pre-damage. The experimental results indicate that the mechanical properties of pre-damaged specimens show large damage differences for different cycles. The damage variable of the pre-damaged specimens increases with the increase in cycle number and confining pressure. The specimen damage is primarily due to the strength weakening effect caused by cycle numbers, and the confining pressure restriction effect is not obvious. The evolution laws of uniaxial compression damage propagation in the pre-damaged specimens show differences and an obvious localization phenomenon. Pre-damaged specimens experienced three failure modes in the uniaxial compression test, namely tensile shear failure (Mode I), quasi-coplanar shear failure (Mode II), and stepped path failure (Mode III), and under different pre-damage stress environments with high confining pressures, the failure modes are dominated by Mode II and Mode III, respectively.

Wang et al. [5] carried out the in situ ground pressure monitoring and numerical simulation calculation using the FLAC2D software, so as to solve the problem of surrounding rock stability control for this roadway type. The influence laws of the surrounding rock lithology, the vertical and horizontal distance between the roadway and overlying working face, the positional relationship between the roadway and the overlying working face, and the support form and strength of the rock surrounding an oblique straddle roadway were obtained. Within the range of mining influence, the properties of the rock surrounding the roof and floor were very different, and the deformation of the rock surrounding the two sides exhibited regional differences. The influence range of the mining working face on the rock floor of the roadway was approximately 30–40 m, and that of horizontal mining was approximately 50–60 m. The mining influence on the rock surrounding the side roadway of the working face is large, but the mining influence on the roadway below is small. Using FLAC2D, the stress and displacement characteristics of the rock surrounding the obliquely straddled roadway were compared and analyzed when the bolt support, combined bolt and shed support, and bolt–shotcreting–grouting support were adopted. Then, the proposed support scheme of bolting and shotcreting was successfully applied. The deformation of the rock surrounding the roadway was satisfactorily controlled, and the results were useful as a reference for similar roadway maintenance projects.

Yu et al. [6] selected Yuanbao Bay Coal Mine, Shuozhou, Shanxi, to study the collapse of the overlying coal pillars on the longwall face and to reveal the mechanism of the pillar collapse and the disaster-causing mechanism caused by strong ground pressure. The results showed that the dynamic collapse process of coal pillars is relatively complicated. First, the coal pillars on both sides of the goaf are destroyed and destabilized, followed by the adjacent coal pillars, which eventually cause a large-scale collapse of the coal pillars. This results in a large-scale cut-off movement of the overlying strata, and the large impact load that acts on the longwall face causes an unmovable longwall face support. Moreover, the roof weighting is severe when strong ground pressure occurs on the longwall face, causing local support jammed accidents. Furthermore, the data of each measurement point of the strata movement inside the ground borehole significantly increase, and the position of the borescope peeping error holes in the ground drill hole rise steeply. The range of movement of the overlying strata increases instantaneously, and all strata begin to move. Research on the mechanism of strong ground pressure can effectively prevent mine safety accidents, thus avoiding huge economic losses.

Liu et al. [7] conducted dynamic flattened Brazilian disc (FBD) tensile tests on naturally saturated sandstone under static pre-tension using a modified split-Hopkinson pressure bar (SHPB) device. Combining high-speed photographs with digital image correlation (DIC) technology, we can observe the variation in strain applied to specimens' surfaces, including the central crack initiation. The experimental results indicate that the dynamic tensile strength of naturally saturated specimens increases with an increase in loading rate, but with the pre-tension increase, the dynamic strength at a certain loading rate decreases accordingly. Moreover, the dynamic strength of naturally saturated sandstone is found to be lower than that of natural sandstone. The fracture behavior of naturally saturated and natural specimens is similar, and both exhibit obvious tensile cracks. The comprehensive micromechanism of water effects, concerning the dynamic tensile behavior of rocks with static preload, can be explained by the weakening effects of water on mechanical properties, the water wedging effect, and the Stefan effect.

Han et al. [8] built the numerical model between different perforation spacing by the extended finite element method (XFEM), so as to reveal the variation in the stress shadow with perforation spacing. The variation in stress shadows was analyzed from the stress of two perforation centers, the fracture path, and the ratio of fracture length to spacing. The simulations showed that the reservoir rock at the two perforation centers is always in a state of compressive stress, and the smaller the perforation spacing, the higher the maximum compressive stress. Moreover, the compressive stress value can directly reflect the size of the stress shadow effect, which changes with the fracture propagation. When the fracture length extends to 2.5 times the perforation spacing, the stress shadow effect is the strongest. In addition, small perforation spacing leads to the backward-spreading of hydraulic fractures, and the smaller the perforation spacing, the greater the deflection degree of hydraulic fractures. Additionally, the deflection angle of the fracture decreases with the expansion of the fracture. Furthermore, the perforation spacing has an important influence on the initiation pressure, and the smaller the perforation spacing, the greater the initiation pressure. At the same time, there is also a perforation spacing which minimizes the initiation pressure. However, when the perforation spacing increases to a certain value (the result of this work is about 14 m), the initiation pressure will not change. This study will be useful in guiding the design of programs related to simultaneous fracturing.

Xiao et al. [9] analyzed the physical and mechanical behaviors of granite treated with different thermal shocks by non-destructive (P-wave velocity test) and destructive tests (uniaxial compression test and Brazil splitting test). The results show that the P-wave velocity (VP), uniaxial compressive strength (UCS), elastic modulus (E), and tensile strength (st) of specimens all decrease with the treatment temperature. Compared with air cooling, water cooling causes greater damage to the mechanical properties of granite. Thermal shock induces thermal stress inside the rock due to the inhomogeneous expansion of mineral particles, and further causes the initiation and propagation of microcracks which alter the mechanical behaviors of granite. Rapid cooling aggravates the damage degree of specimens. The failure pattern gradually transforms from longitudinal fracture to shear failure with temperature. In addition, there is a good fitting relationship between P-wave velocity and the mechanical parameters of granite after different temperature treatments, which indicates that P-wave velocity can be used to evaluate rock damage and predict rock mechanical parameters. The research results can provide guidance for high-temperature rock engineering.

Peng et al. [10] used physical simulation to study the formation and evolution of a normal fault from a strain energy perspective. Based on the similarity principle, we designed and conducted three repeated physical simulation experiments according to the normal fault in the Yanchang Formation of Jinhe Oilfield, Ordos Basin, China, and obtained dip angle, fault displacement, and strain energy via the velocity profile recorded by high-resolution particle image velocimetry (PIV). As a result, the strain energy is mainly released in the normal fault line zone, and can thus serve as a channel for oil/gas migration and escape routes connected to the earth's surface, destroying the already formed oil/gas reservoirs. Thus, one might need to avoid drilling near the fault line. Moreover, a significant amount of strain energy remaining in the hanging wall is the reason as to why the normal fault continues to evolve after the normal fault formation until the antithetic fault forms. Our findings provide important insights into the formation and evolution of normal faults from a strain energy perspective, which plays an important role in oil/gas exploration, prediction of the shallow-source earthquake, and post-disaster reconstruction site selection.

Bao et al. [11] proposed a new method based on the inverse logistic function, considering inverse distance weighting (IDW) to predict the displacement of landslides. Quantitative standards of dividing the deformation stages and determining the critical sliding time were put forward. The proposed method is applied in some landslide cases according to the displacement monitoring data, which shows that the new method is effective. Moreover, long-term displacement predictions are applied for two landslides. Finally, summarized with the application in other landslide cases, the value of displacement acceleration, 0.9 mm/day^2, is suggested as the first early warning standard of sliding, and the fitting function of the acceleration rate with the volume or length of the landslide can be considered as the secondary critical threshold function of landslide failure.

Xiong et al. [12] derived a novel procedure for the coupled simulation of thermal and fluid flow models (NPCTF) to model heat flow and thermal energy absorption characteristics in rough-walled rock fractures. The perturbation method is used to calculate the pressure and flow rate in connected wedge-shaped cells at a pore scale, and an approximate analytical solution of temperature distribution in wedge-shaped cells is obtained, which assumes an identical temperature between the fluid and fracture wall. The proposed method is verified in Barton and Choubey (1985) fracture profiles. The maximum deviation of temperature distribution between the proposed method and heat flow simulation is 13.2% and flow transmissivity is 1.2%, which indicates the results from the proposed method are in close agreement with those obtained from simulations. By applying the proposed NPCTF to real rock fractures obtained by a 3D stereotopometric scanning system, its performance was tested against heat flow simulations from a COMSOL code. The mean discrepancy between them is 1.51% for all cases of fracture profiles, meaning that the new model can be applicable for fractures with different fracture roughness. Performance analysis shows that small fracture aperture increases the deviation of NPCTF, but this decreases for a large aperture fracture. The accuracy of the NPCTF is not sensitive to the size of the mesh.

Peng et al. [13] used a combination of experiment and infrared detection, where the strength, deformation, and infrared temperature evolution behavior of marble with elliptical holes under uniaxial compression were studied. The test results showed that as the vertical axis b of the ellipse increased, the peak intensity first decreased and then increased, and the minimum value appeared when the horizontal axis was equal to the vertical axis. The detection results of the infrared thermal imager showed that the maximum temperature, minimum temperature, and average temperature of the observation area in the loading stage showed a downward trend, and the range of change was between 0.02 °C and 1 °C. It was mainly due to the accumulation of energy in the loading process of the rock sample that caused the surface temperature of the specimen to decrease. In the brittle failure stage, macroscopic cracks appeared on the surface of the rock sample, which caused the energy accumulated inside to dissipate, thereby increasing the maximum temperature and average temperature of the rock sample. The average temperature increase was from about 0.05 °C to about 0.19 °C. The evolution of infrared temperature was consistent with the mechanical characteristics of rock sample failure, indicating that infrared thermal imaging technology can provide effective monitoring for the study of rock mechanics. The research in this paper provides new ideas for further research on the basic characteristics of rock failure under uniaxial compression.

3. Summarize Remarks

The papers presented in this Special Issue cover the important aspects of the latest progress in multifield and multiscale coupling of rock engineering. Even though the multifield and multiscale coupling of rock engineering is an extensive topic, this small contribution could stimulate the community to conduct further research, and thus stimulate progress in this area. Therefore, we believe that the presented papers will have practical importance for future development within rock engineering sector. Finally, together with the other co-Guest Editors, Prof. Junlong Shang and Prof. Manchao He, we wish to thank the authors who contributed their works to this Special Issue.

Funding: This research received no external funding.

Acknowledgments: This research was supported by the Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2022JQ-304), the Opening Fund of State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines (Grant No. SKLMRDPC21KF04). We would like to acknowledge the authors who contributed to this Special Issue.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gao, L.; Kang, X.T.; Gao, L.; Ma, Z.Q. Study of the Stability of the Surface Perilous Rock in a Mining Area. *Energies* **2022**, *15*, 1542. [CrossRef]
2. Gao, D.Y.; Sang, S.X.; Liu, S.Q.; Geng, J.S.; Wang, T.; Sun, T.M. Investigation of the Energy Evolution of Tectonic Coal under Triaxial Cyclic Loading with Different Loading Rates and the Underlying Mechanism. *Energies* **2021**, *14*, 8124. [CrossRef]

3. Santos, J.E.; Carcione, J.M.; Gao, L.; Ba, J. Two-Phase Flow Effects on Seismic Wave Anelasticity in Anisotropic Poroelastic Media. *Energies* **2021**, *14*, 6528. [CrossRef]
4. Hu, J.H.; Zeng, P.P.; Yang, D.J.; Wen, G.P.; Xu, X.; Ma, S.W.; Zhao, F.W.; Xiang, R. Experimental Investigation on Uniaxial Compression Mechanical Behavior and Damage Evolution of Pre-Damaged Granite after Cyclic Loading. *Energies* **2021**, *14*, 6179. [CrossRef]
5. Wang, P.; Zhang, N.; Kan, J.G.; Wang, B.; Xu, X.L. Stabilization of Rock Roadway under Obliquely Straddle Working Face. *Energies* **2021**, *14*, 5759. [CrossRef]
6. Yu, D.; Yi, X.Y.; Liang, Z.M.; Lou, J.F.; Zhu, W.B. Research on Strong Ground Pressure of Multiple-Seam Caused by Remnant Room Pillars Undermining in Shallow Seams. *Energies* **2021**, *14*, 5221. [CrossRef]
7. Liu, X.Y.; Dai, F.; Liu, Y.; Pei, P.D.; Yan, Z.L. Experimental Investigation of the Dynamic Tensile Properties of Naturally Saturated Rocks Using the Coupled Static–Dynamic Flattened Brazilian Disc Method. *Energies* **2021**, *14*, 4784. [CrossRef]
8. Han, W.G.; Cui, Z.D.; Zhu, Z.G. The Effect of Perforation Spacing on the Variation of Stress Shadow. *Energies* **2021**, *14*, 4040. [CrossRef]
9. Xiao, P.; Zheng, J.; Dou, B.; Tian, H.; Cui, G.D.; Kashif, M. Mechanical Behaviors of Granite after Thermal Shock with Different Cooling Rates. *Energies* **2021**, *14*, 3721. [CrossRef]
10. Peng, X.F.; Deng, H.C.; He, J.H.; Chen, H.D.; Zhang, Y.Y.; Kashif, M. Research on the Evolution and Damage Mechanism of Normal Fault Based on Physical Simulation Experiments and Particle Image Velocimetry Technique. *Energies* **2021**, *14*, 2825. [CrossRef]
11. Bao, L.L.; Zhang, G.C.; Hu, X.L.; Whang, S.S.; Liu, X.D. Stage Division of Landslide Deformation and Prediction of Critical Sliding Based on Inverse Logistic Function. *Energies* **2021**, *14*, 1091. [CrossRef]
12. Xiong, F.; Zhu, C.; Jiang, Q.H. A Novel Procedure for Coupled Simulation of Thermal and Fluid Flow Models for Rough-Walled Rock Fractures. *Energies* **2021**, *14*, 951. [CrossRef]
13. Peng, Y.Y.; Lin, Q.C.; He, M.C.; Zhu, C.; Zhang, H.J.; Guo, P.F. Experimental Study on Infrared Temperature Characteristics and Failure Modes of Marble with Prefabricated Holes under Uniaxial Compression. *Energies* **2021**, *14*, 713. [CrossRef]