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Editorial

Analytical, Numerical and Big-Data-Based Methods in Deep Rock Mechanics

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With the increasing requirements for energy, resources and space, numerous rock engineering projects (e.g., mining, tunnelling, underground storage, and geothermal and petroleum engineering) are more often being constructed and operated in large-scale, deep underground and complex geology environments. Meanwhile, more and more unconventional rock failures and rock instabilities (e.g., rockbursts, large-scale collapses and mine earthquakes) are occurring and severely threatening the safety of underground operations. It is well-recognized that rocks have multi-scale structures from minerals, particles, fractures, fissures, joints and stratification to faults and involve multi-scale fracture processes. In the deep earth, rocks are commonly subjected to complex high-stress and strong-dynamics disturbances simultaneously, providing a hotbed for the occurrence of unconventional rock failures. In addition, there are many multi-physics coupling processes in rock masses, such as the coupled thermo-hydromechanical interaction in fractured porous rocks. It is still difficult to understand rock mechanics and to characterize rock behaviors with complex stress conditions, multi-physics processes and multi-scale changes. Therefore, the prevention and control of unconventional instability in deep rock engineering remains a great challenge. The primary aim of this Special Issue "Analytical, Numerical and Big-Data-Based Methods in Deep Rock Mechanics" is to bring together original research discussing innovative efforts on analytical, numerical and big-data-based methods in rock mechanics. It includes 22 manuscripts that illustrate the richness and challenging nature of deep rock mechanics.

The article written by Zhang et al. [1] aims to address the difficulty in obtaining the mechanical parameters of surrounding rocks and large experimental errors, and an optimized BP neural network model is proposed in this paper. The optimized BP neural network model (MEA-BP model) takes advantage of the mind evolutionary algorithm and the neural network. It can not only avoid the local extreme value problem but also improve the accuracy and reliability of the prediction results.

The article published by Li et al. [2] aims to explore the risk of fault-induced water inrush under different mining advancing directions through numerical modeling and investigation. The findings showed that, for a water-conducting fault, the waterproof coal pillar size of mining advances from the hanging wall should be larger than that from the foot wall.

The purpose of the study proposed by Wu et al. [3] was to determine the effects of strain rate and temperature on the dynamic mechanical parameters, energy dissipation features and failure modes of granite. Their study results indicate that the dynamic compressive strength of granite increases exponentially with strain rate and decreases with increasing temperature. The dynamic elastic modulus decreased obviously with increasing temperature but did not have a clear correlation with the strain rate. Under the same incident energy, as the temperature increased, the reflected energy increased notably and the absorbed energy increased slightly, but the transmitted energy decreased. At the same

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temperature, the reflected and absorbed energies increased linearly as the incident energy increased, whereas the transmitted energy increased logarithmically.

The article written by Song et al. [4] developed a reliability model to elucidate the trend of impact-related pipeline damage due to submarine slides. A probability analysis method of impact-related pipeline damage attributed to submarine slides based on the copula function was proposed. Furthermore, the copula function could reasonably characterize relevant the nonnormal distribution characteristics of risk variables and could simulate samples conforming to the distribution pattern of the risk variables.

The article published by Zhai et al. [5] investigated the mechanism of slurry diffusion in horizontal fractures of fractured aquifers; additionally, a one-dimensional seepage grouting theoretical model considering the temporal and spatial variation in slurry viscosity under a constant grouting rate was established. In this model, the grouting pressure required by the predetermined slurry diffusion radius could be obtained by knowing the grouting hole pressure and injection flow.

The article written by Zhao et al. [6] investigated the mining stress evolution law of inclined backfilled stopes in deep mining. Their study demonstrated that mining-induced stress will move to the upper stopes and the stratum below the deepest stope. The transfer range and degree of influence of mining-induced stress will increase with an increase in deep mining, resulting in the most dangerous backfilled stope occurring one or two layers above the deepest stope and the apparent stress concentration area occurring below the deepest stope.

The study by Chen et al. [7] proposed a genetic algorithm (GA) and back propagation (BP) neural network-based computational model for SWB design parameter optimization. This computational model can comprehensively reflect the relation among geological conditions, design parameters and results. Moreover, it automatically searches for the optimal blasting design parameters through the control of SWB targets.

The article published by Chen et al. [8] established a series of models to understand the fracture features of zonal disintegration and to reveal the failure mechanisms of circle tunnels excavated in deep jointed rock masses. The results demonstrate that the zonal disintegration process is induced by the stress redistribution; the dip angle of the joint set has a great influence on the stress buildup, stress shadow and stress transfer as well as on the failure mode of the surrounding rock masses; the existence of parallel and random joints lead the newly formed cracks near the tunnel surface to developing along their strikes; and the random joints make the zonal disintegration pattern much more complex and affected by the regional joint composition.

The article written by Li et al. [9] proposed a novel machine learning model, deep forest, to predict rockburst risk. The deep forest model achieved 100% training accuracy and 92.4% testing accuracy, and it has a more outstanding capability to forecast rockburst disasters compared with other widely used models.

The paper published by Liu et al. [10] studied the effect of lithology on the mechanical and damage behaviors of concrete in a concrete–rock combined specimen (CRCS). The results show that the low-strength concrete part plays a major role in the fracture behavior of CRCS. Furthermore, damage in the CRCS mainly formed in the concrete part, and the extent of the damage in the concrete part was positively correlated with the strength of the rock part.

In the paper published by Zhang et al. [11], the reactive transportation and distribution morphology of a uranium-containing solution was described, a stress-dependent reactive transport model was developed, and the simulator of FLAC3D-CFD was employed. The results show that the uranium-containing solution transport and distribution are significantly dependent on the evolution of the connected channel in a rough-walled fracture, which is significantly influenced by the confining stress and hydraulic pressure.

The article written by Wang et al. [12] proposed a method of rock drillability evaluation based on drilling process monitoring (DPM) parameters. The two-dimensional regression analysis was utilized to investigate the relationships between the drilling parameters, and

the three-dimensional regression analysis was used to establish models of ROP and specific energy (SE). Finally, a prediction model for the uniaxial compressive strength (UCS) was established based on the SE and drillability index. The results show that both the regression models and the prediction models have good performances, which can serve as important guides and a source of data for field drilling and excavation processes.

The article published by Dong et al. [13] analyzed changes in the b value during a rock failure and investigated the b value characteristics of acoustic emission events. The results indicated a higher accuracy of the b value when calculated using the average amplitude setting for an interval between acoustic emission events of 200 or greater, a stress magnitude of 20 MPa or greater, and a stress proportion of 10% or greater.

The article published by Ullah et al. [14] used three approaches—t-distributed stochastic neighbor embedding (t-SNE), K-means clustering, and extreme gradient boosting (XGBoost)—to predict short-term rockburst risk. The classification accuracy of XGBoost was checked using several performance indices. The results of the proposed model serve as a great benchmark for future short-term rockburst level prediction with high accuracy.

The purpose of the article by Wang et al. [15] was to investigate the evolution of the physical and mechanical properties of coal subjected to salty solutions. The results show that the corrosion effect of a salty solution on coal samples becomes stronger with increasing immersion time. The degree of deterioration in the longitudinal wave velocity (vp) is positively correlated with the immersion time.

The article written by Sun et al. [16] investigated the criteria for determining the critical damage of rocks in a constitutive RHT, and the mechanical parameters of metamorphic sodium lava were substituted to obtain the critical damage threshold of rocks in a numerical simulation. The results show that rock clip production has an inhibitory effect on the development and propagation of blast-induced cracks. The fitting results serve as an important reference value for the design of one-time completion blasting of an upward blind shaft.

The article published by Rong et al. [17] evaluated the seismic performance of geosynthetic-reinforced soil structures (GRSSs) of high concrete face rockfill dams (CFRDs) from a stochastic perspective. The result shows that GRSSs can reduce mild damage on CFRDs during earthquakes and can restrain moderate and severe damage. The influence of vertical spacing and the length of GRSSs on the seismic performance was also obtained and provides a reference for the seismic design and risk analysis of CFRDs.

The article written by Sun et al. [18] designed a new ensemble classifier combining a random forest classifier (RF) and the beetle antennae search algorithm (BAS) that was applied to improve the accuracy of rockburst classification. The results show that BAS could tune the hyperparameters of RF efficiently, and the optimal model exhibited a high performance on an independent test set of rockburst data and new engineering projects.

In order to study the diffusion mechanism of foamed polymer slurry in rock fissures, the article published by Liang et al. [19] derived a radial diffusion model of polymer single crack grouting in consideration of factors such as grouting volume, crack width and expansion rate. The findings show that the results of the slurry diffusion radius, pressure and velocity distribution at different times under different working conditions in the model are in good agreement with the analytical solution.

In order to accurately classify the stability of the slope rock mass in an open-pit mine, the article published by Yang et al. [20] established a new stability evaluation model of the slope rock mass based on variable weight and matter–element extension theory. The results show that the classification results of the proposed model are in line with engineering practices and are more accurate than those of the hierarchical-extension model and the multi-level unascertained measure-set pair analysis model.

The article written by Yin et al. [21] focused on a numerical approach to finding the p–y curves for laterally loaded piles. The p–y curve results from this new approach were compared with the typical design equations of API (American Petroleum Institute) and Matlock. Finally, the influence of clay content on the p–y behavior was investigated using

the implemented MATLAB code. When y < 0.15B, the same lateral capacity values resulted in clay contents of 27.5% and 55%, and they were higher than the ones with 0% clay content. The p–y curves showed a decreasing trend with increasing clay content after y > 0.15B.

The article published by Tan et al. [22] investigated the triangle interpolation method for the calculation of the mapping functions of plates containing an opening with arbitrary shapes with an improved method for point adjudgment during iterations. The results show that the stability and failure pattern of the rock mass is correlated with stress around the opening, which is affected by the opening shape. The existence of an opening also greatly reduces the enhancing influence of confining stress on rock specimens.

The article published by Sun et al. [23] presented two-dimensional, closed-form solutions for locating heat-concentrated sources using temperature differences for known and unknown temperature gradient systems. These proposed analytical solutions can provide a new approach to locating heat sources for more complicated conditions using temperature differences, such as the localization of geothermal sources and nuclear waste leak points.

To sum up, the guest editors hope that the selected papers will help scholars and researchers to push forward the progress in analytical, numerical and Big-Data-based methods in deep rock mechanics.

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References

1. Zhang, J.; Li, P.; Yin, X.; Wang, S.; Zhu, Y. Back Analysis of Surrounding Rock Parameters in Pingdingshan Mine Based on BP Neural Network Integrated Mind Evolutionary Algorithm. *Mathematics* **2022**, *10*, 1746. [CrossRef]
2. Li, C.; Xu, Z. Numerical Modeling and Investigation of Fault-Induced Water Inrush Hazard under Different Mining Advancing Directions. *Mathematics* **2022**, *10*, 1561. [CrossRef]
3. Wu, Y.; Huang, L.; Li, X.; Guo, Y.; Liu, H.; Wang, J. Effects of Strain Rate and Temperature on Physical Mechanical Properties and Energy Dissipation Features of Granite. *Mathematics* **2022**, *10*, 1521. [CrossRef]
4. Song, L.; Ying, H.; Wang, W.; Fan, N.; Du, X. Reliability Modelling of Pipeline Failure under the Impact of Submarine Slides-Copula Method. *Mathematics* **2022**, *10*, 1382. [CrossRef]
5. Zhai, M.; Ma, D.; Bai, H. Diffusion Mechanism of Slurry during Grouting in a Fractured Aquifer: A Case Study in Chensilou Coal Mine, China. *Mathematics* **2022**, *10*, 1345. [CrossRef]
6. Zhao, Y.; Zhao, G.; Zhou, J.; Cai, X.; Ma, J. Mining Stress Evolution Law of Inclined Backfilled Stopes Considering the Brittle-Ductile Transition in Deep Mining. *Mathematics* **2022**, *10*, 1308. [CrossRef]
7. Chen, Y.; Chen, S.; Wu, Z.; Dai, B.; Xv, L.; Wu, G. Optimization of Genetic Algorithm through Use of Back Propagation Neural Network in Forecasting Smooth Wall Blasting Parameters. *Mathematics* **2022**, *10*, 1271. [CrossRef]
8. Chen, B.; Gong, B.; Wang, S.; Tang, C. Research on Zonal Disintegration Characteristics and Failure Mechanisms of Deep Tunnel in Jointed Rock Mass with Strength Reduction Method. *Mathematics* **2022**, *10*, 922. [CrossRef]
9. Li, D.; Liu, Z.; Armaghani, D.J.; Xiao, P.; Zhou, J. Novel Ensemble Tree Solution for Rockburst Prediction Using Deep Forest. *Mathematics* **2022**, *10*, 787. [CrossRef]
10. Liu, K.; Jin, S.; Rui, Y.; Huang, J.; Zhou, Z. Effect of Lithology on Mechanical and Damage Behaviors of Concrete in Concrete-Rock Combined Specimen. *Mathematics* **2022**, *10*, 727. [CrossRef]
11. Zhang, T.; Nie, X.; Song, S.; Hao, X.; Yang, X. Modeling Uranium Transport in Rough-Walled Fractures with Stress-Dependent Non-Darcy Fluid Flow. *Mathematics* **2022**, *10*, 702. [CrossRef]
12. Wang, S.; Tang, Y.; Cao, R.; Zhou, Z.; Cai, X. Regressive and Big-Data-Based Analyses of Rock Drillability Based on Drilling Process Monitoring (DPM) Parameters. *Mathematics* **2022**, *10*, 628. [CrossRef]
13. Dong, L.; Zhang, L.; Liu, H.; Du, K.; Liu, X. Acoustic Emission b Value Characteristics of Granite under True Triaxial Stress. *Mathematics* **2022**, *10*, 451. [CrossRef]
14. Ullah, B.; Kamran, M.; Rui, Y. Predictive Modeling of Short-Term Rockburst for the Stability of Subsurface Structures Using Machine Learning Approaches: T-SNE, K-Means Clustering and XGBoost. *Mathematics* **2022**, *10*, 449. [CrossRef]

15. Wang, M.; Guo, Q.; Tian, Y.; Dai, B. Physical and Mechanical Properties Evolution of Coal Subjected to Salty Solution and a Damage Constitutive Model under Uniaxial Compression. *Mathematics* **2021**, *9*, 3264. [CrossRef]
16. Sun, B.; Zhang, Z.; Meng, J.; Huang, Y.; Li, H.; Wang, J. Research on Deep-Hole Cutting Blasting Efficiency in Blind Shafting with High In-Situ Stress Environment Using the Method of SPH. *Mathematics* **2021**, *9*, 3242. [CrossRef]
17. Rong, Z.; Yu, X.; Xu, B.; Du, X. Reliability Analysis of High Concrete-Face Rockfill Dams and Study of Seismic Performance of Earthquake-Resistant Measures Based on Stochastic Dynamic Analysis. *Mathematics* **2021**, *9*, 3124. [CrossRef]
18. Sun, Y.; Li, G.; Yang, S. Rockburst Interpretation by a Data-Driven Approach: A Comparative Study. *Mathematics* **2021**, *9*, 2965. [CrossRef]
19. Liang, J.; Ma, S.; Du, X. Diffusion Model of Parallel Plate Crack Grouting Based on Foaming Expansion Characteristics of Polymer Slurry. *Mathematics* **2021**, *9*, 2907. [CrossRef]
20. Yang, S.; Xu, Z.; Su, K. Variable Weight Matter–Element Extension Model for the Stability Classification of Slope Rock Mass. *Mathematics* **2021**, *9*, 2807. [CrossRef]
21. Yin, K.; Li, L.; Di Filippo, E. A Numerical Investigation to Determine the p–y Curves of Laterally Loaded Piles. *Mathematics* **2021**, *9*, 2783. [CrossRef]
22. Tan, L.; Ren, T.; Dou, L.; Yang, X.; Wang, G.; Peng, H. Analytical Stress Solution and Numerical Mechanical Behavior of Rock Mass Containing an Opening under Different Confining Stress Conditions. *Mathematics* **2021**, *9*, 2462. [CrossRef]
23. Sun, D.; Wu, Y.; Dong, L.; Luo, Q. Closed-Form Solutions for Locating Heat-Concentrated Sources Using Temperature Difference. *Mathematics* **2022**, *10*, 2843. [CrossRef]