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Editorial

Geomechanics for Energy and the Environment

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Geological energy is an abundant source of energy on Earth, encompassing both fossil and non-fossil forms such as oil, natural gas, coal, geothermal energy, shale gas, and coalbed methane. The development of these energy sources has served as a sustained driving force for the advancement of human society and remains a crucial factor in global progress. Coal, a traditional fossil energy source, played a significant role in the early stages of industrial development worldwide, serving as the catalyst for economic growth. Despite the current emphasis on transitioning to green energy, coal continues to be the primary energy source in certain countries, holding a dominant position in energy production and utilization. Researchers have long been devoted to the advancement of coal mining technology, particularly focusing on safe and efficient mining practices as well as disaster prevention. Green mining and intelligent mining are currently at the forefront of research endeavors. Additionally, as mineral resource extraction ventures delve deeper [1], the exploration of deep mining technology has emerged as a frontier of investigation. Furthermore, deep sea mining [2] is also included in this context.

These studies primarily focus on specific research areas, including the intellectualization of deep mining, innovation in mining methods, rock mechanics, coal rock dynamics, rockburst disaster prevention [3–6], prevention of large deformation disasters, and the impact of coal mining on human health. The mechanical properties of rocks exhibit significant variations at different depths and temperatures [7,8]. Notably, Zhang et al. [9] proposed a novel test method and concept of deep rock mechanics to elucidate the evolution mechanism of the surrounding rock's mechanical behavior after the excavation of roadways deeper than 1000 m. Jiang et al. [10] investigated the effects of temperature on the shear behavior of coupled structures during high-stress conditions in deep mining. Yang et al. [11] employed the SPH-FEM coupling simulation method to numerically analyze the influence of ground stress on the fracture of rock due to blasting and the subsequent radiation of seismic waves. Sainoki et al. [12] proposed a method for simulating the seismic activity of spatially distributed faults. Another example is the widespread use of fracking technology in gas drainage, which has yielded positive results in numerous coal mines. However, the absorption of fracturing fluid into coal seams may have adverse effects [13]. Mine disaster prevention and control, mine management, and ecological environment restoration are also vital research areas [14]. Underground mining can lead to surface subsidence to a certain extent [15]. For instance, the management of solid waste generated from coal preparation poses a significant environmental challenge in coal-producing regions worldwide [16]. The deformation and failure of coal and surrounding rock due to mining disturbances represent direct forms of disasters. Coal mine fires, for example, have become a global issue, resulting in severe casualties, environmental damage, and wastage of coal resources [17].

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The deformation and failure of coal and rock are outcomes of energy-driven thermodynamics [18]. Wang et al. [19] conducted indoor experimental research on rockburst under true triaxial conditions, using granite as the study specimen. Another study by Wang et al. [20] examined the mechanical damage evolution of rock columns in underground engineering subjected to seismic loads. Shi et al. [21] investigated the failure mode and load acoustic emission (AE) digital image correlation (DIC) response of coal backfill composite material structures. The creep characteristics of coal pillars remaining from previous mining operations directly influence the long-term stability of underground engineering [22], making it a subject of scholarly interest. Niak et al. [23] explored the application of long-distance directional drilling (LRDD) in the Staszic-Wujek hard coal mine in the Upper Silesia coal basin in Poland. Namjesnik et al. [24] focused on studying the impact of mining on public safety. Shekarian et al. [25] examined the correlation between different mining parameters and the prevalence of pulmonary tuberculosis (CWP) among coal miners.

Coalbed methane refers to the hydrocarbon gas found within coal seams, which is primarily composed of methane and classified as an unconventional natural gas. It mainly adsorbs onto the surface of coal matrix particles, exists partially free within coal rock pores or fractures, or dissolves in coal seam water. It represents a semi mineral resource associated with coal. The development and utilization of coalbed methane offer significant economic benefits. The permeability of coal seams stands as a crucial factor in the efficient extraction of coalbed methane. Consequently, together with the hardness and integrity of the coal seams themselves, it has become a significant research focus in coalbed methane development. Simultaneously, the advancement of mining technology must align with the geological occurrence and structural characteristics of coal seams. For example, the cap rock plays a vital role in trapping coalbed methane reservoirs [26]. It is worth noting that coal seams buried at depths exceeding 1000 m are commonly referred to as deep coalbed methane reservoirs. The mining of coalbed methane is increasingly focused on these deep coal seams, presenting mining technology challenges and escalating geological disaster risks associated with high ground stress. Relevant research is centered around coalbed methane extraction technology, the physical and mechanical properties of coal seams and surrounding rocks, and the permeability behavior of coal seams. For example, Zhang et al. [27] conducted a gas release test on gas-containing coal under conventional triaxial compression conditions, indirectly determining the dynamic effective stress during the gas release process by utilizing the constitutive equation and coal deformation. Yang et al. [28] observed the non-Darcy flow of coalbed methane in fracture systems with high permeability and proposed mathematical and numerical models to examine the effects of non-Darcy flow using the Forchheimer non-Darcy model.

The development of shale gas has emerged as a prominent focus within the energy research field [29,30]. The advancement of horizontal well drilling, completion, and fracturing technology plays a vital role in shale gas development. Horizontal drilling and fracking represent core technologies in this domain. For example, some studies have indicated that [31], unlike the stable injection method used in conventional fracking, employing a variable injection flow rate for unstable fluid injection can yield significant dynamic effects, ultimately enhancing the effectiveness of the fracturing process. Determining the optimal application of these fracturing technologies in formations with varying geological structures and activity levels poses a challenging problem that requires urgent exploration. In particular, the exploitation of shale gas is gradually delving into deeper reservoirs. The presence of deep high ground stress, elevated temperatures, and high permeability environments pose new technical challenges to shale gas development. While addressing technological innovations, these factors also increase the costs associated with shale gas exploitation. Environmental concerns during shale gas exploitation must not be overlooked, including issues such as water and shale gas leakage, contamination of formations due to fracturing fluid, and the potential for induced seismicity resulting from fracking shale reservoirs. These mining and environmental challenges represent important areas of research. Su et al. [32] conducted an evaluation of the impact of underground deformation caused by longwall mining on the integrity of shale gas well casing, as well as the safety and health of underground miners. This assessment was based on research findings from the National Institute of Occupational Safety and Health (NIOSH) spanning the years 2016 to 2019.

Oil serves as the primary energy source for numerous countries worldwide. The demand for such resources across various sectors of society is immense, and the effectiveness and output of oil extraction are determined by the application of oil extraction technology. The utilization of advanced technology can enhance the efficiency of resource development and utilization, thus fostering social progress. Horizontal well drilling stands as a crucial technology employed in the oil extraction stage, enabling the drilling of wellbores along designated directions. Simultaneously, geographic information system (GIS) technology, utilizing computer software and hardware, is employed to gather surface information and geographic data. Through analysis and processing, GIS technology assists in oil extraction operations. Chemical flooding, gas flooding, thermal oil recovery, and microbial oil recovery are significant technologies in petroleum development. However, it is crucial to acknowledge that petroleum is not a clean energy source, and its extensive utilization is accompanied by ecological and environmental challenges. These issues primarily manifest as soil, atmospheric, and water resource pollution. Consequently, it becomes imperative to implement proper treatment methods for wastewater, exhaust gas, and solid waste generated during the oil extraction process. Researchers have conducted relevant studies on efficient oil extraction technologies as well as environmental protection measures in response to these concerns.

Geothermal energy is a renewable and clean energy source that exists beneath the Earth's surface. Hot dry rock refers to a rock mass buried at a depth of 2–6 km, with temperatures ranging from 150 to 650 °C and lacking water or steam. The reserves of hot dry rock are abundant, with the thermal energy stored in it accounting for about 30% of the total proven geothermal resources. This amount surpasses that of steam, hot water, and other geothermal resources, even exceeding the combined thermal energy of coal, oil, and natural gas. The enhanced geothermal system (EGS) is an artificial geothermal system that economically harnesses geothermal energy from deep, low-permeability hot dry rock by artificially fracturing geothermal reservoirs. However, the CO_2 enhanced heat recovery system (CO_2-EGS) was proposed by Brown, utilizing CO_2 as a heat exchange medium instead of water and injecting it into the formation. In this context, CO_2 primarily functions in flow and heat exchange processes. Furthermore, the injection of CO_2 in the CO_2-EGS process leads to the presence of residual CO_2 within the formation, and the engineering also aims to effectively seal the CO_2. However, numerous challenges arise in practical EGS projects. For example, it becomes essential to address issues such as accurately predicting fracture morphology and expansion during fracking, enhancing hydraulic connectivity between water injection wells/CO_2 injection wells and production wells, mitigating excessive water/CO_2 loss due to crack expansion, and effectively preventing and controlling geological damage and earthquake disasters during the mining process. These issues represent valuable areas of study in the development of deep hot dry rocks. Yang et al. [33] utilized ANSYS Workbench to simulate changes in residual magma heat and investigated the distribution characteristics of geothermal anomalies in the Qianjiaying mine, along with their corresponding geological control factors. Hu et al. [34,35] conducted various heat treatment and mechanical experiments on granite and limestone, focusing on deep geothermal development to analyze changes in the physical and mechanical properties of geothermal reservoirs. Jin et al. [36] carried out experimental research on physical properties like the permeability of granite. Feng et al. [37–39] extensively studied the characteristics of water injection mining in deep geothermal reservoirs and examined the mechanical properties of granite under thermal cycling conditions with different cooling methods.

The exploration, development and utilization of geological energy, as well as the environmental challenges associated with energy development, encompass multiple disciplines. Hence, we have pursued this topic to gather relevant research on energy development technologies, energy storage techniques, and environmental protection. A specific focus lies particularly on the concept and advancement of new energy geotechnical technology. This includes understanding the underlying mechanisms to safeguard the environment during energy exploration and utilization, ensuring the long-term safety of energy storage, and promoting the sustainable utilization of energy resources. The main subjects covered by this topic include, but are not limited to, the following:

- ➢ Multiphase flow and transport in porous media;
- ➢ Carbon dioxide sequestration and hydrogen storage in geological formations;
- ➢ Mathematical modeling and numerical simulations of coupled processes;
- ➢ Development, storage, and transportation of unconventional oil and gas;
- ➢ Prevention and mitigation of geological disasters in mining;
- ➢ Mathematical challenges in rock mechanics and rock engineering;
- ➢ Production and storage of geological energy;
- ➢ Environmental protection in resource development;
- ➢ Application of machine learning to address complex energy and environmental problems.

This topic will encompass a broad range of research fields, including the development technology of oil, coal, natural gas, shale gas, coalbed methane, and geothermal energy, as well as their utilization and storage. Special attention will be given to addressing environmental protection issues. We invite research findings related to geological energy development, utilization, storage, sustainable development, and the interplay between energy development and environmental protection to be published on this topic.

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