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Editorial

Sustainable Development in Green Mining and Geotechnical Engineering—An Overview

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1. Introduction

The sustainable development of green mining and geotechnical engineering has become a crucial area of study in light of the increasing global efforts toward environmental conservation and responsible resource extraction. This Editorial synthesizes the findings of the 20 research papers published in this Special Issue, which offer significant contributions to the advancement of sustainable development practices within geotechnical and mining engineering. These studies address challenges such as groundwater preservation, carbon sequestration, and the mitigation of environmental damage caused by resource extraction, etc.

2. Special Issue Content

Longwall backfill mining helps to preserve groundwater by limiting the height of the water-conductive fractured zone (HWCFZ), but faces challenges related to filling time, space, and coordination with mining activities. A new method called continuous extraction and partial backfill (CEPB) has been proposed by Xu et al. [1] to address these issues. The analytic hierarchy process (AHP) used in their study identified five key factors affecting HWCFZ: the hard-rock lithology ratio, mining height, mining depth, and the widths of protective blocks and the blocks used in the Wongawilli method. Applied in a colliery in the Yu-Shen mining area, the model's results closely matched field measurements. This model was further generalized to the whole mining area, resulting in a thematic map of the HWCFZ including the protective zone thickness. A water-preserving mining criterion based on the equivalent permeability coefficient of the protective zone was proposed to optimize the CEPB mining parameters.

Red mud (RM), a byproduct of the Bayer process, poses several environmental risks due to its large production volume. However, its high iron content makes iron recovery a promising solution by reducing RM waste while generating economic benefits. Kong et al. [2] reviewed three methods to recover iron from RM: physical, chemical, and emerging approaches. The physical methods (e.g., gravity separation and magnetic separation) are energy-efficient but offer low iron recovery rates and produce concentrates with a low iron content (TFe). Chemical methods include hydrometallurgy (acid leaching) and pyrometallurgy (thermochemical reactions). Hydrometallurgy yields high recovery rates but is complex and costly due to the use of acid. Pyrometallurgy, particularly the reduction of Fe_3O_4 in fluidized beds, has lower energy consumption and reaction times but results in lower-TFe concentrates, requiring further research. Emerging methods are environmentally friendly but are still being tested at the lab scale, requiring further studies into process efficiency, cost assessment, and scalability. While they are promising in the long term, significant research is needed for their application within the industry.

The water-conducting fracture zone (WCFZ) is vital for preventing roof water damage in mines. Yin et al. [3] used data from 52 boreholes in the Ordos Basin to identify four key factors influencing WCFZ height: mining thickness, hard rock proportion, working

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width, and mining depth. Unitary function models were developed for each factor, with mining thickness being the most significant. A multiple regression model was created using the gray correlation and fuzzy comparison methods, with an error margin below 10%. The model was applied to the Qingshuiying Coalfield to predict the height of the WCFZ based on borehole data, revealing an increasing trend from southeast to northwest. A 3D hydrogeological model was also developed to visualize the spatial distribution of the WCFZ and its relationship with overlying aquifers. This method effectively predicts WCFZ height, helping to mitigate risks from water gushing in mines while improving ecological protection.

The multicomponent transient electromagnetic method (TDEM) offers significant advantages for exploration. Through simulation and field experiments in a copper–nickel mining area, Wang et al. [4] found that the horizontal component effectively points to the center of low-resistivity ore bodies, while the vertical component has strong coupling with the ore body, aiding in quantitative inversion. Both components provide consistent results, reducing the limitations of the traditional method for interpreting a single vertical component and improving field efficiency. Although terrain variations led to some errors in measuring the inversion depth, the interpretation remains accurate. The horizontal component's zero-contour intersection consistently points to the ore body's center, enabling a faster identification of anomaly orientation and reducing field data acquisition costs. The multicomponent analysis improves reliability and overcomes the limitations of using just the vertical component for interpretation. This approach enhances the accuracy and efficiency of exploration in complex terrains.

Zhang et al. [5] addresses the intertwined challenges of ecological damage from coal mining and greenhouse gas emissions in large coal power plants. Focusing on a coal power base in northwest China, the authors propose a green mining model that captures carbon dioxide in goafs (abandoned mine voids) using backfill strips made from solid mine waste. These strips, composed of gray bricks made from aeolian sand and fly ash, are strengthened through carbonization curing, which enhances their bearing strength. The researchers analyzed surface subsidence within and the overburden stability of mines with different backfill strip configurations. The results indicate that increasing the strip width and decreasing the spacing between strips significantly improves surface subsidence, fracture propagation, and gas tightness, facilitating carbon dioxide sequestration. This research offers a promising model for environmentally friendly mining practices and the low-carbon utilization of coal resources.

Pang et al. [6] address the uneven deformation of gangue-filled walls and other challenges in providing large-scale roadway support to mining areas. A failure mechanics model of bagged gangue was developed, and uniaxial compression tests showed that gangue particles between 0 and 20 mm offer strong support, meeting technical requirements for gob-side entry. Wet shotcrete demonstrated superior deformation capacity compared to dry shotcrete, providing greater toughness under load. Additionally, the optimal spray layer thickness for flexibility and support was determined to be around 80 mm. The research offers solutions for cost-effective, environmentally friendly coal mine waste disposal while also improving structural integrity.

The governance of abandoned mines is a critical issue in China, where utilizing these sites offers a solution that aligns with the country's goals of ecological protection and carbon reduction. Du et al. [7] reviews global advancements in abandoned mine utilization, focusing on four primary models: energy storage, waste treatment, ecological restoration, and CO_2 sequestration. Applications include pumped storage, gas/oil storage, CO_2 storage, radioactive waste disposal, and the development of tourism. Despite the potential of China's abandoned mines, most utilization technologies are still in the research phase due to complex geological challenges. Learning from developed countries like the U.S., Germany, and the U.K., China must invest in key technologies and establish industrial demonstration projects. By addressing rock mechanics issues and creating sustainable business models, China can advance the reuse of abandoned mines to contribute to ecological civilization and meet its carbon goals.

Li et al. [8] introduces a novel strain of *Acidithiobacillus ferrooxidans* (YQ-N3) that was isolated from river sediment that was polluted by acid mine drainage (AMD) from an abandoned mine in Shanxi, China. Genome sequencing revealed that YQ-N3 has a 3.2 million base pair genome, comprising one circular chromosome and five plasmids, including a newly discovered plasmid that has not been recorded in any of the major databases. YQ-N3 shares close evolutionary ties with *A. ferrooxidans* ATCC23270 and *A. ferridurans* JCM18981 and contains multiple genes related to iron and sulfur metabolism. Laboratory experiments demonstrated YQ-N3′s ability to significantly enhance Fe^{2+}, S^0, and FeS_2 oxidation, improving the hydrophilicity of sulfur. In biological desulfurization tests, it achieved a 62.25% sulfur removal rate in coal by removing pyrite and organic sulfur. This strain offers promising applications in industrial desulfurization, biometallurgy, and AMD treatment, providing a foundation for future research and environmental management strategies.

Pan et al. [9] analyzes the stability of the Tongling tailings impoundment during the remining process, focusing on the impact of recovery height and various working conditions. Using a combination of engineering surveys, laboratory tests, and 2D and 3D numerical simulations, their study examines how dam stability can evolve. Key findings include the following: (1) Lower recovery heights improve dam stability by lowering the infiltration line, but poor drainage increases risks, particularly during floods. (2) As mining height decreases, the dam's safety factor improves, maintaining overall stability. (3) Extreme conditions, such as floods or earthquakes, reduce safety by increasing shear stress and displacements. (4) The research underscores the effectiveness of advanced simulations using 2D and 3D software to model the dam's behavior and predict risks. This approach has significant global implications for safely managing tailings dams, emphasizing the need for regular maintenance of drainage systems to ensure stability during recovery operations.

Chen et al. [10] examine the impact of wetting–drying cycles on the deterioration of cemented paste backfill (CPB) used in open-pit coal mines. CPB samples, made with marl particles, Portland cement, sulfoaluminate cement, and gypsum, were tested under various wetting–drying cycles. The results showed that the CPB underwent shear and tensile coalescence in the early cycles and shear coalescence in the later cycles. Both unconfined compressive strength (UCS) and elastic modulus (EM) decreased with increasing cycles and porosity, with EM being more sensitive to the gypsum content. The deterioration process was divided into initial and secondary stages, with the evolution of damage following an 'S' curve. This research proposes a highwall filling mining method to improve resource recovery and promote sustainable coal resource exploitation by utilizing solid waste. It also provides valuable insights into CPB design for open-pit mines.

Aeromagnetic measurements are key in mineral exploration, but unmanned aerial vehicles (UAVs) produce maneuvering noise that affects data accuracy. To address this, aeromagnetic compensation is essential. Traditional compensation models based on linear regression face multicollinearity, leading to inconsistent results across different flight directions. Bi et al. [11] introduce an adaptive model-based method to suppress UAV aeromagnetic noise by assigning model variables based on flight heading characteristics, reducing multicollinearity's impact. By automatically selecting significant variables with lower multicollinearity, the optimal compensation model is developed, improving accuracy. Testing on a UAV platform in Ma'anshan demonstrated that this adaptive algorithm outperformed traditional methods, yielding fewer errors and a higher improvement ratio. This research effectively solves the multicollinearity issue, enhancing the robustness and accuracy of aeromagnetic data compensation. This method has proven to be valuable for precise magnetic anomaly detection, aiding further inversion and interpretation in mineral exploration.

Wang et al. [12] explore the impact of open-pit coal mining on surrounding vegetation in arid and semi-arid regions, focusing on vegetation phenology. Using high-frequency time series data from Landsat 8 and Sentinel-2, the study quantifies several key phenological phases: the Start of Season (SOS), the End of Season (EOS), and the Length of Season (LOS). The results show exponential changes in these phases as the distance from the mining areas increases. Mining causes delayed greening, early senescence, and shorter growth cycles. The disturbance range varies by mine, with HDG-HEWS, MX, and XD affecting SOS up to 1625 m and EOS up to 825 m. Mineral dust is a major factor in these disruptions. Overlapping mining areas intensify the disturbance, increasing the impact on vegetation cycles. These findings provide valuable insights for dust control and ecological restoration, helping to mitigate mining's environmental effects.

Wang et al. [13] employ three-dimensional resistivity and chargeability tomography using a distributed data acquisition system to explore new ore bodies in the Huaniushan region of China. Utilizing expanding-gradient and pole–dipole arrays, the research established a high-resolution geoelectric model that correlates well with known geological formations, indicating potential mineralization in low-resistivity and high-chargeability zones. The study emphasizes the advantages of true 3D tomography over quasi-3D methods, highlighting the importance of varied transmitter directions and vector signal collection for accurate modeling. While the true 3D inversion yielded better results, it also highlighted limitations associated with using isotropic inversion algorithms in anisotropic conditions, suggesting the need for further algorithm development. The research advocates for a balanced approach to designing acquisition schemes, weighing spatial resolution, signal quality, and cost-effectiveness, to enhance early-stage exploration and detailed investigations in mineral exploration.

Bai et al. (Contribution 1) examine mining fractures that are critical for water conservation in mining and the stability of coal mining subsidence areas, as well as the restoration of surface ecosystems. Using the key strata theory and analyzing overburden failure, their research reveals the formation mechanisms of "saddle-shaped" water-conducting fracture zones and they identify that permanent mining fractures concentrate at the working face boundaries. Through shear testing of sandstone, it was found that rock damage correlates positively with shear stress, indicating structural stability in the overburden. The fracture zone can be categorized into original fractures, tensile fractures, structural voids, and void compaction areas, with the structural void area showing the greatest deformation. A regional division method based on overburden critical failure was applied and validated through surface movement monitoring, demonstrating that subsidence near the working face boundaries exceeds that in the middle, emphasizing the long-term nature of residual surface deformation and its significance for safe mining and ecological restoration.

The novel continuous extraction and partial backfill (CEPB) mining method effectively addresses the issues associated with traditional longwall backfill mining by reducing the height of the water-conductive fractured zone (HWCFZ) and conserving groundwater. Xu et al. (Contribution 2) utilize the Analytic Hierarchy Process (AHP) to identify five key factors affecting HWCFZ: the hard-rock lithology ratio, mining height and depth, and the widths of Wongawilli and protective blocks. A numerical model was developed to simulate HWCFZ variations, leading to a predictive model validated with field measurements. The model was generalized for broader application within the Yu-Shen mining area, producing thematic maps of the HWCFZ including protective zone characteristics. Additionally, a criterion based on the equivalent permeability coefficient of the protective zone was established to guide mining parameter optimization for water-conservation efforts in Northwest China; as such, future studies should focus on mining-induced permeability changes.

Li et al. (Contribution 3) investigate the performance evaluation of green mining (GM) in underground gold mines, focusing on achieving a balance between mineral resource exploitation and environmental protection. An evaluation criteria system tailored towards underground gold mines is developed in their study, comprising four key criteria and twenty indicators. The integrated gray DEMATEL and ANP methods are employed to assess the green mining performance (GMP), accounting for the correlations between indicators. Case studies of six underground gold mines reveal significant differences between traditional and pilot green mines, highlighting areas for improvement. The study identifies the integral elements of GM, such as safety, resource utilization, environmental protection, and mining efficiency, while analyzing the weaknesses and strengths of each mine. A cause–effect analysis further categorizes the indicators based on their prominence and relationships, guiding targeted improvements. The study acknowledges limitations, such as the need for additional evidence to validate the proposed methods, but overall the evaluation framework provides valuable insights for mining management and government policy, with potential applicability to similar underground metal mines and broader evaluation contexts.

Wu et al. (Contribution 4) address the critical need for appropriate development strategies for the mining industry's green transition by introducing a novel integrated decision support model. It employs a combined SWOT analysis and PEST framework to evaluate the internal and external factors influencing green mining. The fuzzy analytic hierarchy process (AHP) quantitatively assesses factor weights, while the fuzzy Measurement of Alternatives and Ranking according to Compromise Solution (MARCOS) method ranks development strategies. The optimal strategy identified is to "grasp the trend of green development and improve the protection and exploitation level of mineral resources". A comprehensive analysis led to the identification of four main criteria and sixteen subcriteria, from which eight macro strategies were formulated. The methodology's robustness is confirmed through comparative and sensitivity analyses. This study is pioneering in its quantitative approach to SWOT-PEST analysis, providing a systematic framework for selecting green mining strategies. Its implications extend beyond mining, offering insights for strategic decision-making in various industries. Future research may explore extending these fuzzy analysis methods further.

The mining industry has severely impacted land and ecological environments, prompting a surge in literature focused on land reclamation and ecological restoration (LRER). Shao et al. (Contribution 5) analyze 2357 articles from the Web of Science database using the Bibliometrix R-package to evaluate LRER research from 1990 to 2022. Their key findings indicate a gradual increase in both the number of publications and citations over this period. Their high-frequency keyword analysis reveals that heavy metal pollution remediation is a prominent research area, while the cluster analysis identifies two main themes: heavy metal pollution and the ecological restoration of mining areas. A study of the thematic evolution of the field highlights ongoing research in mine drainage treatment, soil reconstruction, and vegetation restoration. Future research directions should include exploring the links between ecological restoration, carbon sequestration, and biodiversity, alongside enhancing international cooperation and technological exchanges. The analysis indicates that countries such as China, the USA, Australia, Canada, and Germany lead LRER research efforts, with a significant number of collaborations between them being present. This study provides a comprehensive overview of the LRER literature, offering valuable insights for future research.

Artisanal gold mining (AGM) is essential yet often overlooks operational efficiency and financial analyses, focusing primarily on environmental and social impacts, particularly the use of mercury. Marin et al. (Contribution 6) investigates the sustainability of mercury-free AGM operations by examining various parameters, including company interactions, production logistics, and geological planning. The findings reveal that AGM remains unsustainable even without mercury, primarily due to inadequate planning and operational inefficiencies. While much research emphasizes the health effects of mercury and the need to formalize operations, this study underscores the significance of operational efficiency and comprehensive mine planning. For AGM to be sustainable, it must simultaneously address social, economic, and environmental factors and implement a robust mine planning cycle that incorporates geological knowledge. By enhancing these strategies, AGM operations can achieve greater stability, similar to that of medium or large mining enterprises, providing insights for governments and communities to improve AGM sustainability through effective planning and operational enhancements.

To support economic growth, ecological protection, and carbon neutrality goals, green mine construction has become crucial in China. Du et al. (Contribution 7) review the significance of mineral resources and summarize the experiences of and sustainable development directions for green mines, providing insights for the global mining sector. Their study introduces the management processes currently used in China and outlines four green mine models: green technology mining, operation modernization, stability mining, and ecological restoration. Key construction elements include resource utilization, energy conservation, and technological innovation. Despite the establishment of over 1250 national green mines and notable advancements, challenges such as regional imbalances and inadequate policies persist. Future efforts require collaboration between governments, enterprises, and society, emphasizing tailored policies and the development of low-carbon technologies to achieve sustainable mining practices and enhance the quality of the industry's development.

3. Closing Remarks

The studies reviewed in this Editorial represent significant advancements in the field of sustainable geotechnical and mining engineering. Through innovative methods such as continuous extraction and continuous backfill (CECB), carbon sequestration, and advanced numerical modeling, these research efforts contribute to reducing the environmental impact of mining while ensuring operational efficiency and safety. By integrating water-preserving techniques, carbon sequestration, and structural stability measures, these studies pave the way for more sustainable and responsible resource extraction practices. As these methods are further refined and implemented on a larger scale, they have the potential to revolutionize the mining industry, making it more environmentally friendly and economically viable. The findings presented in these 20 papers serve as a foundation for future research and development on sustainable geotechnical and rock engineering.

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