Original Research Article

Stability prediction and safety control of surrounding rock in deep mining based on digital twins

Zidong Lu
Yunnan Vocational Institute of Energy Technology, Qujing, Yunnan, 655001, China

Abstract: Deep mining encounters complex working conditions such as high ground stress, strong disturbance, and multi field coupling. Disasters caused by rock instability occur frequently, and traditional monitoring and control methods suffer from lag and insufficient accuracy, which cannot meet the requirements of safe deep mining. Digital twin technology can create a virtual copy of the rock support system, achieve virtual and real synchronization, dynamically deduce and implement intelligent control. Starting from the actual situation of deep mining engineering, this article analyzes the relevant factors of rock stability and the shortcomings of traditional control, discusses the application advantages of digital twin technology, focuses on exploring its application in dynamic prediction of rock stability, multi field coupling simulation, and intelligent safety control, and provides specific measures to promote the implementation of technology.

Keywords: deep mining; digital twin; rock stability; predictive warning; safety regulation; multi-field coupling

1. Introduction

As shallow mineral resources gradually deplete, mining depths continue to deepen. At this time, the surrounding rock exhibits characteristics such as deep high ground stress, high permeability, and strong mining disturbance. The risk of deformation, rock burst, collapse, and other disasters in the surrounding rock increases significantly, which severely limits the development of deep mining towards safety and efficiency. In the past, the control of surrounding rock relied on manual observation, static models, and empirical judgment, which had shortcomings such as scattered data, slow prediction, and passive adjustment, making it difficult to accurately describe the dynamic changes of surrounding rock. Digital twin technology creates real-time correspondence between physical objects and virtual models, integrates monitoring data from multiple sources and mechanical simulations, and has key functions of dynamic perception, trend prediction, and intelligent adjustment, bringing new methods to deal with deep surrounding rock stability problems.

2. Shortcomings in traditional control of surrounding rock in deep mining

The traditional rock stability control mode is no longer suitable for complex working conditions in deep mining, with prominent shortcomings. Monitoring mainly relies on single point discrete monitoring, often using equipment such as stress meters and displacement meters. The data coverage is small, the synchronization is poor, and it is difficult to capture the overall deformation and stress changes of the surrounding rock in all directions. Manual collection efficiency is low, errors are large, and data timeliness is insufficient; In terms of prediction, relying on static mechanical models and empirical formulas greatly simplifies the model parameters, which cannot accurately describe the dynamic changes of surrounding rock under the coupling effect of multiple deep fields. The prediction accuracy is low, the lag is strong, and it is difficult to predict disaster risks in advance; In terms of regulation, most of them are passive prevention and control, often strengthening and supporting remedies after disasters occur, lacking the ability for dynamic regulation beforehand. The design of support parameters relies on experience and is

difficult to meet the stable conditions of the surrounding rock at that time. It is easy to have insufficient or excessive support, which can cause resource waste and hidden safety risks.

3. The application advantages of digital twin technology in deep mining surrounding rock control

3.1. Realize dynamic perception of all elements of surrounding rock state

The digital twin technology, combined with the Internet of Things, 5G, and sensor technologies, has created a multi-source three-dimensional detection network that can dynamically perceive the state of deep surrounding rock in all directions and all weather conditions. Intelligent sensors such as stress, displacement, microseismicity, seepage, temperature, etc. are set up at key parts of the surrounding rock to collect data on changes in rock stress, deformation displacement, crack propagation, groundwater seepage, and many other aspects at any time. The data is quickly transmitted to the digital twin platform through the 5G private network, thus breaking through the limitations of traditional monitoring data fragmentation and delay.

3.2. Improve the accuracy and timeliness of rock stability prediction

By relying on the digital twin rock prediction model, breaking through the limitations of traditional static models, dynamic and high-precision prediction effects can be achieved. The model is based on a high-precision three-dimensional geological model, integrating rock mechanics parameters and multiple field coupling equations to form a virtual twin model that develops in the same way as the physical rock. It can reflect the changes in the stress field, displacement field, and seepage field of the rock in real time. By using big data analysis and machine learning algorithms, it trains on past observation data and disaster instance data, identifies the changing rules of rock instability, and creates a dynamic prediction model.

3.3. Supporting intelligent and precise control of surrounding rock safety

The digital twin technology creates an integrated closed system of "perception prediction regulation", which promotes the transformation of rock safety regulation from passive remediation to active prevention and control, from experience led to intelligent decision-making. Through virtual models, different mining parameters and support schemes are simulated to simulate the changes in rock stability, and multiple schemes are compared and simulated to improve excavation speed, mining sequence, support stiffness and other parameters, and develop exclusive regulation schemes.

4. Practical path for stability prediction and safety control of surrounding rock in deep mining based on digital twins

4.1. Constructing a high-precision digital twin model of surrounding rock

Model creation is a key foundation for the application of digital twin technology, which requires step-by-step precise modeling and dynamic updates. Firstly, geological drilling, geophysical exploration, tunnel measurement and other data are integrated, and 3D geological modeling technology is used to reproduce the deep rock strata structure, faults, joints and other geological structures, forming a detailed geological skeleton model. Secondly, combined with rock mechanics experimental data and geostress detection data, mechanical parameters such as rock elastic modulus, Poisson's ratio, and cohesion are assigned to the model to create a rock mechanics characteristic model. Thirdly, real-time monitoring data is added to achieve millisecond level synchronous mapping between virtual models and physical rock masses, and the model status is updated in a timely manner to accurately depict the dynamic changes of rock masses. This provides high-precision virtual support for stability prediction and control.

4.2. Multi field coupling simulation and dynamic stability prediction

By relying on digital twin models for stress seepage temperature damage multi field coupling simulation, dynamic prediction and risk classification of surrounding rock stability can be achieved. According to numerical calculation methods such as finite element and discrete element, multiple

field coupling control equations are added to the twin model to simulate the entire process of rock stress redistribution, deformation and failure, and crack propagation when deep high ground stress, groundwater seepage, temperature changes, and mining agitation work together. Combined with microseismic monitoring data, micro rupture events inside the surrounding rock can be identified, the location of rupture and the law of energy release can be analyzed, and the possibility of rock burst, collapse and other disasters can be inferred in advance.

4.3. Intelligent control and closed-loop optimization of surrounding rock safety

Create an intelligent regulation system for surrounding rock safety triggered by digital twins, achieving a cyclic operation of "monitoring warning regulation feedback". According to the stability prediction results, different risk level areas will automatically correspond to regulation strategies: Stable areas will continue to be monitored and supported regularly; Improve support parameters in basic stable areas and increase key monitoring; Implement pre-treatment measures such as pre pressure relief and grouting reinforcement in potential unstable areas; Immediately terminate operations in unstable areas and adopt emergency measures such as strong support and partial closure. During adjustment, monitor the changes in the surrounding rock state at any time, return the adjustment results to the digital twin model, dynamically improve the adjustment parameters, and create a cyclic improvement mechanism to ensure the stability and controllability of the surrounding rock.

5. Technical application guarantee measures

5.1. Strengthen multi-source data fusion and quality control

Establish a standardized data collection, transmission, and processing system, standardize sensor layout, data formats, and transmission protocols to ensure compatibility and consistency of multi-source data, improve data quality control levels, and eliminate abnormal data through data cleaning, denoising, verification, and other operations to ensure data authenticity, reliability, and completeness. Create a data security protection system, utilizing encryption transmission, permission control, backup and recovery technologies to prevent data leakage and loss, ensure data security, and provide reliable data support for the precise operation of digital twin models.

5.2. Strengthening technology integration and talent team construction

Promote the deep integration of digital twins with technologies such as the Internet of Things, big data, artificial intelligence, and numerical computing, solve key technical problems such as multi field coupling simulation, real-time data synchronization, and intelligent decision-making algorithms, improve technical adaptability and stability, attach importance to personnel cultivation, form a composite team that includes knowledge from multiple disciplines such as mining engineering, rock mechanics, and information technology, conduct specialized training in digital twin modeling, platform operation, simulation analysis, etc., and enhance personnel's technical application level; Attract professional and technical talents, improve personnel structure, and provide personnel support for technology implementation.

5.3. Improve technical standards and safety management systems

Develop application standards for digital twin technology in deep mining surrounding rock, standardize model formation, data collection, simulation analysis, and control decision-making, clarify technical indicators and accuracy requirements, promote the standardized application of this technology, create corresponding safety management systems, clarify monitoring, alarm, and control responsibilities for each position, and standardize abnormal handling procedures. Incorporate digital twin control into the conventional safety production and management system, improve equipment protection and management level, regularly calibrate sensors, inspect conveying equipment, and improve platform systems to ensure stable and reliable operation of the digital twin system.

6. Summary

After creating a high-precision digital twin model of the surrounding rock, it is possible to achieve

multi field coupling simulation and dynamic prediction, forming a closed system of intelligent control, thereby accurately determining the risk of rock instability, formulating scientific control plans, and improving the intelligence and precision level of deep mining rock safety control. The article discusses the application advantages and implementation methods of digital twin technology, and provides guarantee methods for data management, personnel training, and institutional improvement, providing practical reference for the prevention of deep mining rock disasters.

About the author

Zidong Lu (1990.02-), Han nationality, Yuxi, Yunnan Province, master, teacher, research direction: research and development of intelligent coal mine equipment.

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