Advances in Key Technologies for Accurate Identification, Monitoring and Early Warning of Disaster Risks in Service Wellbores

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Abstract. Due to the structural transformation of the national macro-economic and policy adjustment of the supply-side structural reform, the number of new coal mine shaft has been sharply reduced. Future coal production capacity mainly focuses on the current mines in operation, therefore, accurate identification and monitoring warning of risk in the service wellbores has become a problem to be solved. This paper summarizes the current research and existing problems of wellbore and explores how to conduct wellbore risk identification and monitoring and early warning and how to handle multi-source disasters. Based on the theory of wellbore deformation system instability and regional geological multi-scale multi-phase multi-field coupling disaster mechanism, engineering risk identification and early warning theory, surrounding the scientific problems of accurate identification and monitoring and early warning of service wellbore risk, this paper puts forward the idea of multi-scale source risk monitoring of service wellbore, and summarizes 4 key scientific issues and 7 main research directions of accurate identification, monitoring, and warning of service wellbore risk. As for the stress source, corrosion source and physical property source that affect the safe service of the wellbore, for the risk hazard such as wellbore cracking, corrosion and deflection, this paper adopts multi-disciplinary and multi-method under the scale of “region-mining area-wellbore-key section” to study the multi-field coupling force and deformation characteristics of the service wellbore. Based on the precursor data collection, multi-network fusion transmission and scientific intelligence analysis technology of big data and cloud computing platform, a new model of future wellbore safety service featuring online real-time monitoring, intelligent identification, and accurate warning of the service wellbore risk can be established, thereby providing theoretical support and technical approach for the safety management and intelligent service of service wellbores in China.

1. Introduction
As a non-renewable resource, coal is both energy and industrial raw materials. In 2016, coal consumption accounted for 62% of China’s total energy consumption [1], A key consulting project called China’s coal resources efficient recycling and energy conservation strategy research issued by Chinese Academy of Engineering predicted that China’s coal production capacity in 2020, 2030, 2050 would be 4.4 billion, 4 billion, 3.4 billion tons respectively [2], so coal’s status as the main energy will
not change for a long period of time. However, due to the country’s macroeconomic structural transformation and policy control in supply-side structural reform, the number of new coal mine wellbore was sharply reduced. Therefore, future coal production capacity mainly depends on production mines. In order to meet the demand for coal resources, safe operation of the service wellbore has become one of the key research topics.

The mine wellbore is the throat and safe passage for deep mining. Service wellbores have different characteristics and complex service environment due to the different rock formation and multi-phase geological body, forming their multi-level, nonlinear and irreversible feature, which seriously affects the safe operation of mines [3]. Therefore, it is of great significance to study the key technologies of accurate identification and monitoring and early warning of service wells. At present, the problem of wellbore degradation such as instability or deflection of the service wellbore, permeable wall, circumferential cracking of the borehole wall, exposition of the steel well, corrosion of the wall and burst tendency of the concrete wall are becoming more prominent, causing huge threat to the normal transportation and safe production of the mine. In order to avoid safety accident brought by the rupture of the wellbore and the economic loss caused by wellbore shutdown, identification of disaster and disaster factors should be conducted as early as possible. Accurate predictions of the classification and evaluation and re-service period should also be carried out in order to provide scientific and theoretical guidance for wellbore management. By evaluating the safety of the service wellbore and the service state of it and predicting its re-service period, preventive measures can be taken at an early stage to avoid the rupture of the borehole wall [4]. At the same time, as mining depth, energy extraction, and demand of national strategy increase, the stability of the wellbore becomes an important issue that requires further study. It is also an important basic research work to ensure mine construction and normal production.

Second, in terms of better transforming and upgrading of the shutdown mines and promoting the comprehensive utilization of special underground space in China, the wellbore is also the only way to enter the underground space. Therefore, the primary task of reusing the mine closed pit is to conduct safety evaluation and re-serving period prediction for the service wellbore and provide data support for evaluation and prediction. Real-time, reliable and information-based monitoring system shall be in place for the wellbore. Reusing closed pit mine wellbore is also in line with the national strategy for sustainable development of transforming and upgrading the mine closed pit. [5]

Third, research on risk analysis and evaluation theory of service wellbore has not yet formed a complete system. Although some scholars have conducted preliminary research, they have only carried out relatively simple analysis and evaluation of specific projects. Importance should be attached to exploring possible hazard factors such as geological environment, hydrological environment, wellbore wall condition and the influence of underground mining disturbance, establishing a systematic and scientific risk analysis theory and evaluation system for service wellbore, and matching it with real-time, effective and stable dynamic monitoring system in the risk management study of service wells.

In view of the complex and unclear disaster-leading conditions of coal mine service wellbore in China, insufficient research on disaster prevention mechanism, and lack of rapid monitoring method and scientific and effective prevention and control technology and equipment, this paper concludes major scientific problems and key engineering and technical problems of mine wall disaster prevention and control of service wellbore, puts forward the idea of precise multi-scale risk identification of the wellbore, multi-scale monitoring and early warning, and establishes the theoretical and technical framework of wellbore risk identification and monitoring and early warning, thus providing a theoretical and technical system for multi-scale source monitoring of the service wellbore and scientific and technical support for its safe operation.
2. Status quo of accurate identification and monitoring and early warning of service wellbore risk

Since the 1980s, accidents concerning coal mine wellbore instability, circumferential cracking of the borehole wall, exposed steel bars have occurred in the mining areas of Xu, Huai, Datun, Yongxia, Zhangzhou, Shanxi, Inner Mongolia, etc., and corresponding research on evaluation and analysis of wellbore stability has also delivered results. However, most of research is based on conceptual establishment and qualitative research. Quantitative research was conducted to calculate and analyze based on the theory of engineering structure reliability. Comprehensive study on the index of engineering technology and economy of wellbore is currently insufficient, and the research on risk analysis and assessment theory of wellbore is still in the preliminary stage. At present, Chinese scholars mostly focus on the failure mechanism or treatment, the fracture of coal mine wall, corresponding prevention measures, wellbore failure prediction theory and application of concrete materials of the wall. Among these studies, new tectonic movement hypothesis, seepage deformation hypothesis, negative friction hypothesis, three-factor synthesis hypothesis, vertical additional force hypothesis, well wall corrosion deterioration are very famous. Undoubtedly, all studies have greatly promoted the research on the rupture wall treatment measures and the new rupture prevention wall structure [6].

2.1 Construction of the wellbore risk assessment system.

Yi Sihai [7] studied the evaluation method of wellbore mining failure. By summarizing the form and characteristics of wellbore mining deformation and failure, based on the relationship between wellbore failure and surrounding rock deformation, he put forward a scientifically feasible evaluation method and index of wellbore mining damage mainly for concrete and reinforced concrete wellbore wall: take the vertical deformation relationship between the wall and surrounding rock as the main evaluation index to establish calculation formula of vertical compression (tensile) deformation and failure of top wall and bedrock section respectively; confirm the reliability of the evaluation method and indicators through the case analysis of the wellbore mining damage. His research solved the problem of safety evaluation of wellbore mining damage and provides a reliable technical guarantee for the safe design of wellbore coal pillar mining. Xu Yanchun [8] further improved the wellbore safety evaluation system. By taking main and auxiliary coal mines, Dongfeng and Xifeng mines in Xinglongzhuang as examples, he used the improved empirical fitting method and the multivariate statistical distance discrimination method to evaluate the stability of the four wellbores in December 2015. In order to further determine the stability of the main wells and increase the accuracy of the evaluation, he took eight main factors affecting the stability of the borehole as the discriminating factors, and collected 11 known results Xinglongzhuang Coal Mine for establishing a mathematical model and further evaluates the predicted samples using the minimum distance discriminant method. Liu Chaolin [9] took Dongtan Mine as an example to analyze the changing characteristics of the main factors affecting the wellbore rupture, evaluate and analyze the current stability of each wellbore in Dongtan Mine, and predicted the time range of the wellbore rupture in order to avoid safety risks and economic losses due to wellbore rupture. This research provides a reference for selecting a reasonable wellbore rupture prevention project. Guan Yunzhang [10] proposed a prediction method for the possibility of wellbore rupture in order to determine the safety of the auxiliary shaft of Xinglongzhuang Coal Mine. His research identifies the possibility of wellbore rupture by considering factors of the compression capacity of the pressure relief groove, the service engineering service life, the dropped water level and the formation compression factor, and improves the accuracy of evaluation and prediction by using changing multi-factor discrimination into single factor discrimination using fuzzy mathematics.

2.2 Theoretical research on wellbore stress.

Yang Weihao [11] focusing on the external load-vertical additional force of the wellbore, solved the elastic solution of the additional force of the borehole wall of the hydrophobic formation by using the elastic theory and assuming no relative sliding between the borehole wall and the formation. Zhou
Guoqing and Cheng Xilu, based on the model test results, used space elastic theory to study the calculation of borehole stress subjected to ground pressure, self-weight and vertical additional force, and concluded the approximate calculation formula of borehole stress. Yao Zhishu [12] conducted a theoretical analysis of the borehole stress under the condition of vertical additional force based on the spatial asymmetry. Liang Huaiqiang [13] used the elastic theory to transform the problem of borehole wall force to a spatial axisymmetric one, and theoretically analyzed the stress state of the borehole wall under the action of local internal pressure (constrained inner wall). In summary, most of the current research is elastic analysis of the spatial axisymmetric problem, the result of which is not suitable for damaged or the nearly damaged well wall. The research on the risk analysis theory of the service wellbore has not started yet.

2.3 Numerical simulation study of wellbore wall.
Yang Junjie [14] calculated and analyzed the stress distribution and ultimate bearing capacity of the borehole wall under uniform and non-uniform load conditions using self-programmed finite element program. Combining the nonlinear constitutive relation with the appropriate concrete strength criterion, he explores how to calculate the limit state of concrete wall theoretically. Yao Zhishu [15] took the well wall damaged in the field as the research object, and reverse calculated the vertical additional force received by the back wall under the normal horizontal side pressure. The result shows that the additional force slightly varies as the parameters of the borehole wall change in the failure of the borehole wall. The additional force value remains in the range of 0.1~0.128 MPa. By comparing it with the result of no-additional stress, he points out that the additional force directly leads to the damage of the borehole wall. Zhou Guoqing [16] used the finite element method to study the relationship between the reinforcement parameters of aquifer, the compressive aquifer and the vertical additional force of the borehole wall and its reduction rate, pointing out that the aquifer’s reinforcement width and distance, the additional force and its reduction rate also change accordingly. Lu Henglin [17] conducted the elastoplastic numerical simulation of the wall rupture caused by the settlement in the deep topsoil. He used the elastoplastic three-dimensional unit for numerical analysis and pointed out that the improvement of material strength and elastic modulus can significantly delay the radial splitting and vertical crushing of the well, with the latter being more significant. Within a certain range, the relationship between the time of radial splitting and vertical crushing of the borehole wall and the strength and elastic modulus of the borehole wall material is not linear. As material strength and elastic modulus increase, the delay effect gradually weakens. In the design of the borehole wall, improving the concrete marking should be considered as the primary method to prevent wall rupture. In summary, most of the current numerical simulation research focuses on the ultimate bearing capacity of the borehole wall. The stress state of the borehole wall under different conditions and its evolution laws need further study.

2.4 Wellbore physics test research
Zhou Guoqing [18] conducted a simulation test on the borehole force under the conditions of bottom drainage on the large-scale multi-functional test bench of the underground engineering laboratory of China University of Mining and Technology. The results confirmed for the first time the existence of vertical additional force that the soil imposed on the borehole wall and concluded the variation of the force with the mine drainage and the distribution along the axial direction of the wellbore. Hong Boqian [19] analyzed the frictional resistance between the borehole wall and the stratum under different wall filling conditions, and proposed that after fully considering the deepening of the wellbore or the opening of the horsehead door, the filling section should be reasonably divided according to the stratum conditions while the additional force should be reduced by using corresponding filling materials and techniques. Yao Zhishu [20] proposed a new type of collapsible drilling well wall structure by focusing on the failure mechanism of well wall under the condition of stratum settlement. The simulation test shows that under this condition, the structure of the wall can be compressed, thereby correspondingly reducing the vertical additional force acting on the well wall and
ensuring its safety. According to this, the design method of the vertical bearing capacity of the shrinkable drilling well wall is proposed and applied in the Huaibei mining area. The above shows that research on the stress state at different depths of the borehole wall, especially the stress state and evolution law of the wellbore rupture process, is not enough. Ji Hongguang [21] studied the corrosion damage of mine wells in Linyi and Tongting and analyzed the occurrence of groundwater in the mine and its main factors of corrosion. Combining the law and process of change of service stress in the mine, he studied the damage and failure mechanism and predicted the reliability and durability of the mine wall with working stress and chemical environment. Liu Juanhong [22,23] et al. studied the transient failure of concrete similar to rockburst under deep complex stress conditions. She studied and tested the compressive strength, splitting tensile strength, dynamic failure time, elastic energy index, impact energy index and acoustic emission parameters of concrete with different strength grades, pointing out that the brittleness coefficient, dynamic failure time and impact energy index should be regarded as the index for concrete impact tendency.

2.5 Field measurement of service wellbore.
Zhou Guoqing [24] carried out a large scale of field-straining test on the additional stress on wellbore wall in the newly built or built wellbore in Xuzhou and Datun mining areas, and accumulated abundant data of change of additional strains of the well with the change of temperature and other conditions. These data covers both the evolution trend of the additional strain of the wellbore under long-term hydrophobicity of the oil-bearing stratum and the data of the stress-strain change of the borehole wall after the nearly damage of the wellbore, wall rupture, and the grouting during formation and treatment. Yang Weihao and Huang Jiahui also carried out field research in Zhangzhou and other mining areas. These researches obtained the development trend of the wellbore force, and played an important role in the dynamic control and guiding the implementation of the grouting reinforcement in the wellbore rupture controlling project, ensuring the safety of the borehole wall during management process of the wellbore rupture disaster.

Therefore, current research mainly analyzes specific wellbore conditions and the wellbore stability. At the same time, there are few selected influencing factors while a single mathematical method or empirical method is often used, which leads to incomprehensive and unreasonable adjustment based on the reality of mines. There is also rare involvement of scientific inference and prediction of future changes in the borehole wall, thus a complete, scientific and unified evaluation system has not been formed.

3. Main problems in accurate risk identification and the monitoring and early warning of the service wellbore
(1) The external risk hazard of the service wellbore is complicated, and the mechanism of the disaster is still unclear.

The service wellbore risk is a nonlinear dynamic process of steady state accumulation and unsteady state release of surrounding rock and borehole system energy under specific geological conditions and a multi-physics coupling disaster-leading process of external load, self-load, wall structure, interaction between borehole wall and surrounding rock and physical and mechanical properties of surrounding rock during its service. The mechanism of risk evolution is one of the most highly regarded research topics in the academic world. It not only relates to the structure of the borehole wall and its interaction with the surrounding rock, but also relates to the fault-fold structure and tectonic stress distribution. It is worth noting that as the depth of the wellbore increases, it is also related to the nonlinear dynamic evolution process of wellbore wall stress changing and energy surging under the coupling condition of the tectonic stress field and the mining stress field. Since the risk hazard is complicated and the disaster mechanism is still unclear, it is urgent to study the mechanism of multi-phase and multi-field coupling disasters under underground mining conditions, and establish a new theory of risk catastrophe and evaluation of service wellbore.
(2) It is difficult to explore the multi-source disaster-causing information of the service wellbore, thus poor universality.

Present service wellbore risk identification and evaluation models and methods are mainly designed for the analysis and research of a single consistent disaster factor. They have independent applicable conditions without considering the common disaster conditions of such disasters as borehole cracks and well wall degradation, thus cannot be used for coupling analysis or comprehensive warning. Although some risk identification and evaluation models have been established, they are mainly for some parameters that are easier to monitor. Other possible disaster parameters are not selected, so it is difficult to explore the multi-source disaster-causing information of the service wellbore, thus larger deviations in evaluation and early warning models and poor universality and less accurate evaluation and warning. Targeting the strong space-time characteristics of service wellbore risk identification and early warning, it is urgent to study the fast and scientific coupling algorithm for wellbore stress, strain, corrosion evolution, skew, acoustic emission and other test data to achieve the rapid integration and calculation of the index of wellbore wall safety status, forming a multi-source multi-index evaluation method for mode of the wellbore wall in the dangerous area to realize rapid identification and dynamic spotting of the dangerous area of the well wall.

(3) Poor reliability of the sensor for disaster precursor information acquisition, and lack of means of integrating multi-network sensors.

Regionalization, real-time continuity, and intelligent networking of service wellbore condition monitoring technology and equipment are the main development directions. Intelligent identification, scientific analysis and multi-attribute decision making of precursor information are key theories of monitoring and early warning. However, due to the complexity and dynamic evolution of the environment in which the service wellbore is located, the single dimension, poor authenticity and accuracy of the stress, deformation and water pressure monitoring of the borehole wall, and poor timeliness of the corrosion source and corrosion degree of the concrete wall, single forecasting index, poor coupling with other monitoring indicators, and lack of systematic monitoring and early warning system, the existing wellbore sensing and monitoring technology has many problems in terms of reliability, timeliness and compatibility. For example, the internal environment of the wellbore is complicated, leading to difficult transmission, poor mobility, narrow coverage, poor timeliness of wireless transmission, poor anti-interference performance, lack of intensive monitoring and transmission means in key areas, small coverage of wellbore image processing functions, and severe delay in processing. Therefore, it is urgent to study key technologies such as sensors for wellhead disaster information acquisition, multi-network fusion transmission, and real-time image processing of wellbore images to solve the current problems affecting effective risk assessment, such as poor reliability, low sensitivity, small coverage and common network transmission of multi-source information.

(4) Lack of monitoring and early warning of large-scale and regional power disasters.

Present risk identification of service wellbore is highly based on experience. The risk monitoring and early warning system is mainly arranged inside or on the surface of the wellbore wall. The monitoring scale and scope are still small while large-scale and regional wellbore risk monitoring and warning system has not been established. During the service, due to the influence of mining disturbances, the stress field, temperature field, seepage field, energy field and other fields in a certain area and their relationship are a process of dynamic evolution and coupling change. This also leads to wellbore disasters. Therefore, it is urgent to build a multi-scale monitoring and early warning platform to combine wellbore state monitoring and regional power monitoring. Based on the Internet of Things, cloud computing and advanced multi-parameter monitoring theory, it is necessary to establish a real-time remote online monitoring and early warning platform to realize wellbore disaster warning for remote release, supervision and operation and maintenance.
4. Basic principles and methods for accurate risk identification and monitoring and early warning of service wellbore

Accurate risk identification and monitoring and early warning of service wellbore is based on the concept of safe production, evolution mechanism of multi-phase multi-field coupled disaster catastrophe, using disaster precursor information acquisition sensor and multi-network fusion transmission technology, extraction and the decision-making method of multi-scale and multi-attribute precursor information can realize the new mode and new method of depth perception, can realize accurate risk identification and monitoring and early warning of wellbore disaster precursor information. Its principle is shown in Figure 1.

Figure 1. Accurate identification and monitoring and early warning principle of service shaft risk

In order to solve major problems such as multi-source disasters in service wells, complex coupling between disaster sources, and unclear disaster prevention mechanism, it is necessary to adopt a combination of basic theoretical analysis, physical simulation test, mine field test and numerical simulation calculation and advanced information acquisition and transmission and big data analysis technology to carry out technical study concerning mining disturbance and multi-phase and multi-field coupling conditions, the evolution mechanism of well wall deterioration disasters, catastrophic precursor information acquisition and transmission and mining identification. In addition, it is urgent to propose a new theory of risks in multi-phase and multi-field coupled disasters in service wellbore, develop technology and equipment for high-reliability and anti-interference disaster precursor information acquisition sensing and multi-network fusion transmission, and form mining methods and early warning models for obtaining multi-source massive dynamic information based on big data and cloud technology so as to realize online monitoring, intelligent identification and real-time accurate warning of hidden dangers of major disasters such as wellbore cracking, water inrush from wellbore and wellbore deviation. The technical system is shown in Figure 2.
5. Scientific problems and research directions of accurate risk identification, monitoring and early warning of service wellbore

According to the system of accurate risk identification and monitoring and early warning of service wellbore, the disaster induced mechanism, risk identification, monitoring and early warning of serviced wellbore are studied from a multi-scale perspective to form a wellbore risk identification and evaluation system and a platform of risk disaster monitoring and early warning of the service wellbore so as to improve the accuracy of risk hazard monitoring and early warning, propose effective control measures and ensure the safe service of the wellbore.

The author believes that the key scientific problems that need to be solved in the service wellbore risk identification and monitoring and early warning include: (1) the coupling relationship between the formation stratum force-energy-physical parameters and the spatio-temporal evolution law and multi-field coupling synergistic disaster mechanism under the mining disturbance action; (2) Intelligent identification and early warning theory of multi-parameter precursor information for service wellbore risks and disasters; (3) Multi-scale, multi-source precursor information acquisition sensing and multi-network convergence transmission technology and equipment; (4) Early warning methods and techniques for service mine well risk and hazards based on monitoring data and cloud computing technology. For the above four problems, seven main research directions are formed. The logical relationship of the main research directions is shown in Figure 3.
6. Conclusion and outlook
Accurate risk identification and monitoring and early warning of service wellbore are aimed at ensuring long-term safe operation of wellbore. Based on the theory of wellbore deformation system instability, regional geological multi-scale multi-phase multi-field coupling disaster mechanism and engineering risk identification and early warning theory, focusing on the scientific problems surrounding the accurate identification and monitoring and early warning of service wellbore risk, this paper proposes the idea of multi-scale source risk monitoring for service wellbore. It focuses on the stress source, corrosion source and physical property source affecting the safety service of the wellbore and risk hazards such as cracking, corrosion and deflection, studies the multi-field coupling force and deformation characteristics of the service wellbore based on the “region-mining area-wellbore-key section” scale using multi-disciplinary and multi-method monitoring. Coupled with precursor information collection, multi-network convergence transmission and scientific intelligence analysis technology based on big data and cloud computing, a new model of future wellbore safety service featuring online real-time monitoring, intelligent identification and accurate early risk warning of the wellbore can be established. This model ensures the safety management and intelligent service of the service wellbore structure.

Guided by the multi-scale source monitoring of service wellbore risk, closely relating to four scientific problems of accurate identification, monitoring and early warning mechanism and key technological research of service wellbore, research is carried out from seven major aspects: mechanism of regional multi-phase multi-field coupling disaster, mechanism of wellbore structure and surrounding rock interaction, theory and technical system of risk intelligent identification and monitoring and early warning, multi-scale, technology and equipment for sourced precursor information acquisition sensing and multi-network fusion transmission, technology and equipment for topo-split-source monitoring of the service wellbore, rapid identification and classification of hazardous areas in service wells, and regional risk monitoring and early warning system platform for service wellbore based on big data and cloud computing. With research from the above perspectives, the multi-scale monitoring theory and technical system of service wellbore will be formed to improve the ability of intelligent risk identification and accurate monitoring and early warning of service wellbore and ensure the safe and smooth improvement of deep mineral resources.

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