Research on Risk Assessment and Classification Method of Raise Boring Rig

Shouye Cheng[1,2], Guoye Jing[1,2], and Zhaoyang Song[1,2](✉)

[1] Mine Construction Research Branch, China Coal Research Institute, Beijing 100013, China
szhaoyang123@126.com
[2] Beijing China Coal Mine Engineering Co. Ltd., Beijing 100013, China

Abstract. In order to promote risk identification and prevention of raise boring rigs, an index system is constructed, and a risk assessment and classification method is proposed. By analysing the risk factors such as geology, equipment, environment and personnel, we constructed a work breakdown structure and a risk breakdown structure for raise boring rigs based on WBS-RBS method respectively, and also established a coupling matrix for risk identification. Expert evaluation and engineering construction experience are adopted to classify and quantify the occurrence probability and risk degrees. Then a comprehensive identification and classification method for raise boring rigs is proposed and the applicability and measures for risk prevention and control under different risk levels are discussed briefly. The method of risk identification and classification of raise boring rig is applied to the risk assessment of inclined shaft construction in a pumped-storage power station, and the rationality and reliability of the assessment method are verified.

Keywords: risk assessment · risk identification · raise boring rigs · engineering construction · classification method

1 Introduction

Underground mining, urban underground space development, pumped storage power station construction, mountain railway/road tunnel ventilation shafts and other engineering constructions all require the construction of a large number of vertical or inclined shafts connecting the upper and lower levels. According to the needs of underground engineering construction and the restrictions of construction conditions, the bottom-up construction method is usually adopted. Compared with the ordinary sinking method from the ground up and down, this bottom-up method is called the reverse sinking method (Short for the raise method). The corresponding projects of this kind are also collectively referred to as raise shafts [1–3]. Raise rig drilling uses the space and production system of the lower roadway. After the pilot hole is drilled directionally, the reaming bit is connected at the lower level, and then reaming is drilled to form a wellbore. During reaming, the slag falls under its own weight to achieve a large high-efficiency drilling with volume breaking and no repeated breaking [4, 5], which plays an important role in the progress of underground engineering construction and technological development.

S. H. B. D. M. Zailani et al. (Eds.): ICMSEM 2023, 259, pp. 47–57, 2024.
https://doi.org/10.2991/978-94-6463-256-9_6

During the drilling process of the raise boring rig, due to the complexity of the formation conditions, the reliability of the equipment performance and the inadequate management, the risks of deformation, collapse, and water inrush of the wellbore surrounding rock are prominent. Risks such as the stuck of raise rig, deflection of the borehole, and falling of the drill tool can cause equipment damage, material loss, increased workload, and even project scrapping, leading to major economic losses or casualties [6]. Therefore, it is necessary to study the cause of the accident through observation, thinking and analysis of the accident, establish a raise rig drilling risk evaluation model and system, and formulate corresponding risk control measures to reduce the occurrence and loss of accidents. But there is a lot of uncertain and complex factors making the data used to evaluate raise rig drilling construction risks incomplete and inaccurate. Moreover, some risk indicators are not easy to quantify, resulting in the characteristics of randomness and ambiguity in raise rig drilling risk evaluation [7].

Regarding the risk evaluation method of underground engineering construction, domestic and foreign scholars have carried out a lot of research work, which has reference significance for the risk evaluation of raise boring rig drilling. Wang [8] applied the membership theory in fuzzy mathematics to fuzzy comprehensive evaluation, and developed a fuzzy analytic hierarchy process (FAHP) that are suitable for various uncertain problems. Jafar et al. [9] used FAHP to evaluate the construction risk for TBM construction under bad geological conditions. Zhao et al. [10] constructed a two-level fuzzy comprehensive evaluation model for TBM construction risks in deep-buried long tunnels. Gu et al. [11] used a fuzzy comprehensive evaluation model based on entropy weight to analyze the construction risks of the West Qinling Super-Long Railway TBM. Song [12] established the TBM construction risk evaluation model by using the nonlinear fuzzy analytic hierarchy process. Liu [13] conducted a qualitative analysis on the risk of raise well drilling and proposed corresponding prevention and control measures. After data analysis and literature survey, it is noted that there is a lack of quantitative assessment and methods for the drilling risks of raise boring rigs. Therefore, this paper constructs the frame structure and risk index system of raise rig drilling risk analysis, and proposes the method of classification and grading evaluation of raise rig drilling risk. The established new evaluation method was applied to the risk evaluation of the inclined shaft construction of the penstock of Chongqing Panlong Hydropower Station, which verified the rationality and reliability of the evaluation method.

2 Raise Rig Drilling Risk Identification and Index System

The primary task of raise rig drilling risk evaluation is risk identification, determining the influencing factors of raise rig drilling risk analysis, and establishing a scientific and reasonable risk evaluation index system. The work breakdown structure-risk breakdown structure (WBS-RBS) method is used to identify and classify raise rig drilling risks. Work breakdown structure is one of the important professional terms of project management [14, 15]. Its basic principle is to gradually subdivide the construction process into a clear hierarchical structure. The risk breakdown structure is a method of gradually grading the possible risk sources from the large risk sources into various more refined small risk factors, and stopping the decomposition until the risk is too small to be noted.

2.1 Work Breakdown Structure of Raise Rig Drilling

According to raise boring technologies and WBS principles, the process of raise boring construction (W) is divided into two levels: the first level WBS is decomposed into 3 stages including construction preparation (W_1), pilot hole drilling (W_2), and reaming stage (W_3). Combined with the work characteristics of each stage of raise boring rig drilling, different procedures for decomposition are distinguished, and the first-level WBS are decomposed into different second-level WBS according to the procedures. The breakdown structure of the drilling work of the raise rig obtained according to the WBS method is shown in Table 1.

2.2 Risk Breakdown Structure of Raise Rig Drilling

According to the structure characteristics of the wellbore and the RBS principle, the risk source (R) of raise boring rig drilling is divided into two levels of risk:

(1) According to the drilling geological conditions and equipment performance of raise boring rigs, the first-level RBS includes four types: geological risk sources, equipment risk sources, environmental risk sources, and personnel risk sources;
(2) Based on a comprehensive analysis of the drilling risks of raise boring rigs, combined with the general idea of the decomposition of the first-level risk sources, the first-level risk source structure is decomposed into different l the second-level risk structures.

The risk breakdown structure obtained according to the RBS method is shown in Table 2.

2.3 Risk Index System Raise Rig Drilling

According to the developed WBS and RBS, the correlation analysis among each second-level unit is performed to obtain the coupling matrix of the drilling risk identification of the raise rig, as shown in Table 3. Among them, the mutual coupling without risk is recorded as “0”, and the mutual coupling with risks are recorded as “1”.

Through coupling analysis and risk identification of on-site construction experience, the risk factors that fully reflect the raise boring construction are determined firstly, followed by the sort and classification of the existing risk factors, analysis of the probability of risk and the severity of the risk. Finally, the risk indicators and risk levels of the raise rig drilling are determined and shown in Table 4.

2.4 Comprehensive Evaluation and Calculation Method of Raise Rig Drilling Risk

looseline-1In the evaluation index system developed in this study, basic data can be obtained through feasible technical means such as indoor testing, formation detection, equipment monitoring, and engineering field testing. Fuzzy comprehensive evaluation and normalization method are used to quantify the index data. The probability of occurrence of indicator risk is divided into 5 levels and assigned quantitatively as: P = {very

Table 1. Work breakdown structure of raise rig drilling work

Target level	first-level WBS	Serial number	second-level WBS
Work of raise rig drilling(W)	construction preparation (W_1)	(1)	Infrastructure(W_{11})
		(2)	Equipment transportation, positioning, hoisting(W_{12})
		(3)	Assembly and debugging(W_{13})
		(4)	Formation modification(W_{14})
	pilot hole drilling (W_2)	(5)	Breaks the rock by pilot hole drill bit(W_{21})
		(6)	Fluid circulation slag discharge by guide hole(W_{22})
		(7)	Pilot hole deflection control(W_{23})
		(8)	Stability control of pilot hole(W_{24})
		(9)	Pilot hole drill pipe connection and lowering(W_{25})
	reaming stage (W_3)	(10)	Connect the drill rod and reaming bit(W_{31})
		(11)	Rock-breaking drill bit(W_{32})
		(12)	Cooling and dust removal(W_{33})
		(13)	Slag removal(W_{34})
		(14)	Surrounding rock control(W_{35})

low risk, low risk, medium risk, high risk, very high risk$\}$ = $\{0.2, 0.4, 0.6, 0.8, 1\}$. According to expert opinions and on-site construction experience, the risk level is divided into 5 parts and assigned quantitatively as: M = {low, low, medium, heavy, severe} = {0.2, 0.4, 0.6, 0.8, 1}.

With the probability value vector of each risk index occurrence in Table 4 as the row vector [Pi] and the risk degree value vector as the column vector [Mi], the comprehensive evaluation value of the drilling risk of the raise rig can be obtained. In detail, this is

Table 2. Risk breakdown structure of raise rig drilling

Target level	First-level RBS	Serial number	Second-level RBS
Risk of raise rig drilling (R)	geological risk sources (R_1)	(1)	Groundwater situation(R_{11})
		(2)	Rock characteristics(R_{12})
		(3)	Strata construction(R_{13})
		(4)	Ground stress effects(R_{14})
	equipment risk sources (R_2)	(5)	Drilling accuracy(R_{21})
		(6)	Device stability(R_{22})
		(7)	Drill pipe reliability(R_{23})
		(8)	Roller wear resistance(R_{24})
	environmental risk sources (R_3)	(9)	The work site(R_{31})
		(10)	Distance from surrounding buildings (R_{32})
		(11)	Underground space structure(R_{33})
	personnel risk sources (R_4)	(12)	Irregular operation(R_{41})
		(13)	Insufficient construction technology(R_{42})
		(14)	Construction management chaos(R_{43})

expressed as:

$$V = [P_1, P_2, P_3, \cdots, P_{16}] \times [M_1, M_2, M_3, \cdots, M_{16}]^T \tag{1}$$

According to the scoring result calculated by formula (1), the drilling risks of raise boring rigs are graded, and the result set of construction risk grades from high to low is:

$$\{\text{Level I}, \text{ Level II}, \text{ Level III}, \text{ Level IV}, \text{ Level V}\} = \{14 \sim 11.34, 11.34 \sim 6.86, 6.86 \sim 3.5, 3.5 \sim 1.26, 1.26 \sim 0\}$$

According to the raise boring risk classification method developed in this study, comprehensive evaluation of raise boring construction is carried out. When the project is at level I, the project is not suitable for use in raise boring drilling construction. When at level II to III, the mining area should be strengthened for construction management, the technical level of personnel should be improved, and the equipment performance

Table 3. Coupling matrix of raise rig drilling risk identification

First-level index	Second-level index	W_1				W_2					W_3				
		W_{11}	W_{12}	W_{13}	W_{14}	W_{21}	W_{22}	W_{23}	W_{24}	W_{25}	W_{31}	W_{32}	W_{33}	W_{34}	W_{35}
R_1	R_{11}	0	0	0	1	0	1	0	0	0	0	0	0	0	1
	R_{12}	0	0	0	1	1	0	1	1	0	0	1	1	0	1
	R_{13}	0	0	0	1	1	1	1	1	0	1	1	0	0	1
	R_{14}	0	0	0	0	1	0	0	1	0	1	1	0	0	1
R_2	R_{21}	0	0	0	0	1	0	1	1	0	0	0	0	0	0
	R_{22}	1	0	1	0	0	0	1	0	0	1	1	0	0	0
	R_{23}	0	0	0	0	1	0	1	0	1	1	0	0	0	0
	R_{24}	0	0	0	0	1	1	1	0	0	0	1	0	0	0
R_3	R_{31}	1	1	0	0	0	0	0	0	0	0	0	0	0	0
	R_{32}	1	0	0	1	0	0	0	0	0	0	0	0	0	0
	R_{33}	0	0	0	1	0	0	0	0	0	0	0	0	0	1
R_4	R_{41}	0	1	1	0	1	0	1	0	1	1	1	1	1	1
	R_{42}	0	0	1	0	1	1	1	0	1	1	1	0	0	0
	R_{43}	0	1	1	0	1	1	1	0	1	1	1	1	1	1

Table 4. Risk index system and degree of risk of the raise rig drilling

Target level	Indicator level	Serial number	Risk index	Degree of risk
risk of the raise rig drilling(U)	geological risk sources(U_1)	(1)	Missing of circulating fluid(U_{11})	Low
		(2)	The formation collapses and shrinks(U_{12})	High
		(3)	Water flows in the perforated well(U_{13})	High
		(4)	Skewness of guide hole(U_{14})	Severe
	equipment risk sources(U_2)	(5)	Deviation of hole position(U_{21})	High
		(6)	Equipment dumping(U_{22})	Severe
		(7)	Drilling stuck(U_{23})	High
		(8)	Burial of drilling(U_{24})	Medium
		(9)	Drill pipe deformation(U_{25})	High
		(10)	Cutterhead failure(U_{26})	High
		(11)	Drop of drill bit(U_{27})	Severe
	environmental risk sources(U_3)	(12)	Deformation of surrounding buildings (U_{31})	High
		(13)	Wellhead collapsed(U_{32})	Severe
	personnel risk sources(U_4)	(14)	Drilling (hole) falling objects(U_{41})	High
		(15)	Drilling reversal(U_{42})	Severe
		(16)	Failure of assembly and debugging(U_{43})	Medium

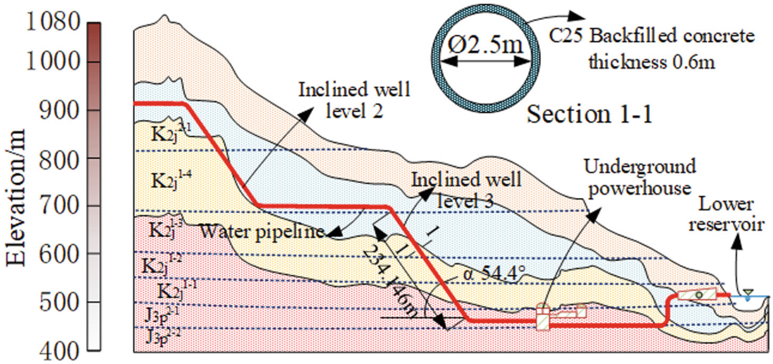


Fig. 1. Section sketch of the inclined shaft

of raise rigs should be optimized along with the stratum modification, drilling support est. Moreover, a complete emergency plan should be established, and then the raise rig drilling construction can be carried out. If at level IV~V, the raise rig drilling can be carried out under the conditions of meticulous management, standardized operation and in place responsibilities.

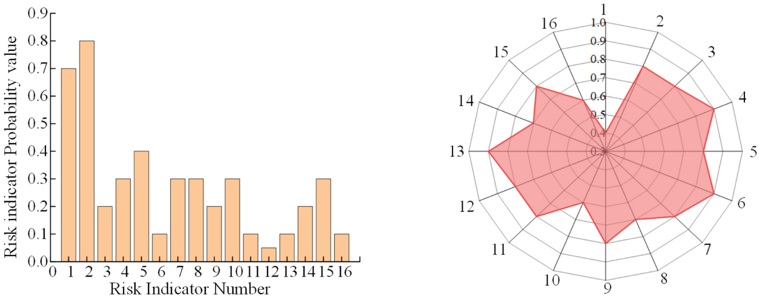
3 A Case Analysis of Engineering

3.1 Overview

In order to verify the rationality and feasibility of the risk assessment and classification method, the proposed method is applied to the raise rig drilling construction of the inclined shaft of the pressure pipeline of the pumped storage power station. The inclined wells of the third stage have a length of 298.96 m, an inclination angle of 55°, and a drilling diameter of 2.4 m. According to the results of geological exploration, the coring results show that the existing geology is mainly the first member of the Jiaguan Formation of the Upper Cretaceous System (K2j1–1, K2j1–2, K2j1–3). The lithology is mainly purple-red siltstone, medium-grained sandstone, and both coarse-grained sandstone and conglomerate. The rock strength is 20–40 MPa, which is easy to be mechanically broken. And the rock integrity Kv is 0.75 ~ 0.35, it belongs to Type II to III surrounding rock according to the Code for Water Resources and Hydropower Engineering Geological Investigation (GB50287-99). The wellbore penetrates the formation and the groundwater is generally underdeveloped. It is dominated by bedrock fissure water, and water seepage along the structure and joint surface can be seen locally. There is no karst developed strata across the wellbore. The schematic diagram of the project layout is shown in Fig. 1.

3.2 Risk Classification and Verification

During the risk assessment and classification of raise boring rigs, the engineering geology, equipment, environment, and personnel parameters of the inclined well will be input into the classification index and evaluation system according to the most unfavorable



(a)Risk indicator Probability value (b)Risk degree value

Fig. 2. The probability of occurrence of each risk indicator and the degree

principle. The rock cutability evaluation result calculated by Formula (1) is 3.2 points with the comprehensive evaluation being at level IV. Therefore, raise boring rig drilling can be carried out with fine management, standardized operation, and responsibilities in place. The value and score of each indicator in the indicator layer are shown in Fig. 2.

According to the actual drilling process of the raise rig and the downhole TV observation results, the raise rig drilled through the relatively broken formation is about 30m in total. The raise boring parameters is 10 rpm and the output pulling force of the raise rig is 1592 kN. Under the formation conditions, the daily footage is 18 ~ 25.0 m, and the well deviation rate is 0.15%. Practice has proved that the drilling risk evaluation and classification method of raise rig developed in this study has certain accuracy and reliability. The evaluation result reflects the degree of risk in raise rig drilling, and can provide guidance for subsequent formation surrounding rock control, drilling rate, the development and implementation of technical plans such as excavation and support, as well as the optimization and upgrading of raise rig equipment.

4 Conclusions

By combining the drilling technology of the raise rig and the WBS-RBS method, a risk index system of the raise rig drilling is developed with the geology, equipment, environment and personnel risk factors being taken into consideration.

Raise rig drilling is a complex mechanical rock-breaking and sinking system. Expert evaluation and engineering construction experience are used to classify and quantify the occurrence probability and risk degree of raise boring rig. With that, a comprehensive risk identification method of raise rig drilling is proposed. According to the calculation results, the drilling risks of raise rigs are classified, and the set of evaluation results from high to low is {level I, level II, level III, level IV, level V}. The applicability and risk prevention and control measures of raise boring rigs under different risk grades are briefly discussed.

The rationality and reliability of the evaluation method is verified by the application of the raise boring rig drilling risk identification and classification methods to the risk evaluation of the inclined shaft construction of the pumped storage power station.

Raise rig drilling risk assessment and classification methods are formulated based on comprehensive analysis of raise rig equipment performance, technical difficulty, technological process, environmental conditions, personnel conditions and geological conditions. It can provide guide to the formulation and implementation of technical or management plans such as prevention and control, surrounding rock stability, construction procedures, and personnel management.

Acknowledgments. This paper is supported by the Special Funds for Technological Innovation and Entrepreneurship of China Coal Science and Engineering Group Co. Ltd. (2021-TD-MS012). The authors thank the anonymous reviewers for their valuable and instructive comments that greatly help improve the quality and completeness of this paper.

References

1. LIU Zhiqiang. Development and prospect of mechanical shaft boring technology[J]. Journal of China coal society, 2013, 38(7): 1116–1122.
2. LIU Zhiqiang, SONG Zhaoyang, CHENG Shouye, et al. Development and prospects of raise boring technologies in China[J]. Coal Science and Technology, 2021, 49(1): 32–65.
3. ZHOU Xing, CHENG Shouye, JING Guoye. Construction technology and application of large diameter deep shaft raise shaft in Xiadian Gold Mine[J]. China Metal Bulletin, 2019 (09): 130+132.
4. Barbara Stack. Handbook of Mining and Tunnelling Machinery[M]. New York: John wiley&Sons.
5. LIU Zhiqiang. Raise Boring Machine[M]. BEIJING: Science press, 2017.
6. JING Guoye. Study on key construction technology of large diameter raise well drilling through special stratum[J]. Coal Engineering, 2019, 51(05): 68–72.
7. AKSOY C O. Review of rock mass rating classification: historical envelopments, application, and restrictions[J]. Journal of Mining Science, 2008, 44(1): 56–68.
8. WANG Peizhuang. Fuzzy set theory and its application[M]. Shanghai: Shanghai Science and Technology Press, 1983.
9. JAFAR K H, KOUROSH S, BAHRAM R, et al. Risk assessment-based selection of rock TBM for adverse geological conditions using fuzzy-AHP[J]. Bulletin of Engineering Geology and the Environment, 2010, 69(4): 523–532.
10. ZHAO Yanxi, XU Wei-ya. Risk assessment of TBM construction for tunnels based on AHP and fuzzy synthetic evaluation[J]. Rock and Soil Mechanics, 2009, 30(3): 793–798.
11. GU Weihong, WANG En-mao, ZHANG Wen-da. Risk assessment on the TBM construction of railway tunnels[J]. Journal of Safety and Environment, 2008, 18(3): 843- 848.
12. SONG Zhanping, GUO Saide, XU Tian,et al. Risk assessment model in TBM construction based on nonlinear fuzzy analytic hierarchy process[J].Rock and soil Mechanics,2021,42(05):1424–1433.
13. LIU Zhiqiang. Risk analysis and prevention and control of reverse well drilling[J]. Journal of Henan Polytechnic University (Natural Science Edition),2016,35:23-27.
14. YANG Yewei. Work breakdown structures of construction project and its applications in engineering[D]. Tianjin: Tianjin University, 2006.
15. HILLSON D, GRIMALDIS, RAFELE C. Managing project risks using a cross risk breakdown matrix[J]. Risk Management, 2006, 8(1): 61–76.