Reliability Analysis of TBM Cutterhead Excavation Based on Belief Reliability

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Abstract. Belief reliability is a reliability measurement method based on opportunity measures, which fully considers the impact of inherent uncertainty and cognitive uncertainty on reliability, and can analyze the reliability of TBM cutterheads. On the basis of the interaction mechanism between the surrounding rock and the cutterhead, the random interference term is introduced to express the cognitive uncertainty, and the parameter relationship equations between the cutterhead penetration and the cutterhead thrust, rock integrity coefficient and axial compressive strength of the rock mass are established, and the confidence reliability margin equation and metric equation are constructed. Combined with the actual case, the analysis results are compared with the reliability considering the uncertainty of the parameters alone, and the reliability advantage of considering the uncertainty is illustrated, and a method to improve the reliability of the tunneling system by increasing the thrust of the cutterhead is proposed.

Keywords: TBM cutter reliability; belief reliability; cognitive uncertainty; margin equation.

1 INTRODUCTION

Tunnel Boring Machine (TBM) is an automated tunnel excavation lining equipment integrating mechanical, hydraulic, laser and electronic technologies [1], which plays a pivotal role in the current hard rock tunnel boring construction. As the core part of TBM tunneling system, the cutterhead mainly has the functions of rock breaking and stabilizing the face, and its reliability directly affects the TBM boring efficiency. According to statistics, the risk accident rate of cutterheads in the TBM boring process accounts for more than half of the total risk accidents of TBM, which has a great impact on excavation efficiency, construction cost and construction risk [2]. Therefore, a reliability study for TBM cutterhead systems is necessary.

Tunnel boring machine cutterhead commonly experiences several types of faults, including cutterhead jamming, tool wear, tool offset wear, cutterhead panel wear, deformation, and damage. The main reason for these issues is the occurrence of large rock masses falling from the excavation face during TBM construction. In the process of rockfall, due to the high compressive strength of the surrounding rock, the fallen rocks are not easily broken, resulting in a significant secondary impact between the

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rocks and the cutterhead during their sliding and the cutterhead's rotation. This can lead to the failure of tool bolts and various other forms of tool damage.

Given the extremely complex working environment of TBMs, there are limitations to on-site measurements and testing of TBMs. XiongYue et al.[3]based on the analysis of 71 excavation accidents, it has been determined that several geological factors are closely related to TBM jamming. These factors include adverse geological conditions, surrounding rock quality, groundwater levels, and in-situ stress. Xu Zhaohui et al.[4]take into account uncertain factors such as cutterhead system assembly, operating position, and geological conditions, a model has been developed to represent the thrust range applied to the cutterhead system. Therefore, it is evident that thrust and geological conditions of the surrounding rock are the primary factors affecting the occurrence of failure incidents.

The uncertainty of the system will exist in the data, model, and verification process is difficult to meet the law of large numbers, the reliability of the uncertain system cannot be well quantified. Norrington et al.[5] studied the calculation of the practical confidence of Bayesian methods. However, this method is based on the assumption of distribution independence, and it is difficult to achieve complete independence in real life. Sun Wei et al.[6] used Monte-Carlo to simulate the reliability of the cutterhead, established the limit state equation of fatigue reliability, and calculated the dynamic reliability of each region of the cutterhead, but did not consider the influence of the welding system on fatigue failure in the modeling process. Lance Fiondellaa et al. [7]found that the independence of component faults has an impact on product reliability, and proposed a statistical confidence optimization model to improve product performance. This shows that the difference between actual confidence and calculation reliability is affected by component independence. Based on this, Zhang Qingyuan et al. [8] identified key performance parameters and analyzed the performance margin, and proposed a new formal analysis method, FPMA method, to apply the performance of the system to measure the reliability. Yuge et al. [9] proposed a reliable calculation process based on performance margin, and applied uncertainty theory to quantitatively calculate the reliability of gear confidence under contact fatigue and bending fatigue, but ignored the influence of cognitive uncertainty, which may cause certain deviations in the calculation process. Wang Haowei[10], Li Xiaoyang [11] revealed the reliability degradation law of time-varying systems by constructing degradation equations based on time-varying normal uncertain distribution. However, no rational explanation of the degradation path was made during the analysis.

Based on the above research, consider that the factors affecting TBM cutterhead boring performance are uncertain. On the uncertain phenomenon of rock machine mutual feeding, this paper proposes a cutterhead reliability study based on confidence and credibility. By determining the main performance indicators and ensuring the reliability discipline equation, the reliability of TBM cutterhead is quantified, and reasonable suggestions are put forward to improve the reliability of the cutterhead.

2 BELIEF RELIABILITY THEORY AND MODELING

2.1 Belief Reliability Theory

Belief reliability [12]is a theoretical system of opportunity measurement based on the combination of probability measure and uncertainty measure, the belief reliability theory, which describes the probability of the operating state of the system in the feasible domain as the reliability of the product. It can be expressed by the following equation.

$$\boldsymbol{P} = f\left(\boldsymbol{X}, \boldsymbol{Y}\right) \tag{1}$$

$$\boldsymbol{M} = d\left(\boldsymbol{P}, \boldsymbol{P}_{th}\right) \tag{2}$$

$$\boldsymbol{P} = f_{\vec{t}}\left(\boldsymbol{X}, \boldsymbol{Y}, t\right) \tag{3}$$

$$R_B(t) = \mu\left(\widetilde{\boldsymbol{M}} > 0\right) \tag{4}$$

Among them, ***X*** is the internal dependent variable (such as equipment parameters and materials), ***Y*** is the external dependent variable (such as environmental conditions), ***P*** describing the functional relationship between the key performance and the internal and external dependent variables. ***M*** is the margin which can be used as a criterion for product failure. $\vec{t}$ is the irreversible degradation time vector that affects the performance P, intrinsic attribute X, and extrinsic attribute Y. μ As an opportunity measure, can be calculated by combining the definitions of uncertain variables, uncertain distributions, inverse uncertain distributions, and related operational rules in uncertainty theory.

Definition 1[13] Uncertainty variable: Suppose that Ω is a nonempty set, L is a σ-algebra on a Ω, and the uncertainty measure M is a set function from L to [0,1]. If ξ is a function from the uncertain space {Ω,L,M} to the set of real numbers R. For any σ-algebraic set B formed by open sets of topological spaces, the set {ξ∈B}={γ∈Ω|ξ(γ)∈B} is an event, then ξ is said to be an uncertain variable. If the function ξ with respect to ω from the probability space (Ω ,A ,Pr) to the set of uncertain variables M{ξ (ω) ∈ B} is measurable , then ξ is said to be an uncertain random variable.

Definition 2[13] Uncertainty distribution: Let ξ be an uncertain variable, then the function Φ(x)=M{ξ ≤ x} is called the uncertain distribution of ξ, and x is an arbitrary real number. For the normal uncertain distribution X~N(e,d) there are:

$$\Phi\left(x\right) = \left[1 + \mathrm{e}^{\frac{\pi(e-x)}{\sqrt{3}d}}\right]^{-1} \tag{5}$$

where e is the mean; d>0 is the standard deviation.

Definition 3[13] Inverse uncertainty distribution: Let ξ represent an uncertain variable with a regular uncertain distribution Φ(x), and call the inverse function $\Phi^{-1}(\alpha)$ of Φ(x) the inverse of ξ the inverse uncertainty distribution of ξ.

Inverse normal uncertain distribution:

$$\Phi^{-1}(\beta)=e+\frac{\sqrt{3}d}{\pi}\ln\frac{\beta}{1-\beta} \tag{6}$$

Let $\xi_1,\xi_2,\ldots,\xi n$ be an independent list of regular uncertainty variables with uncertainty distributions of Φ_1, $\Phi_2,\ldots,\Phi_n$. If the function $f(x_1,x_2,\ldots,x_n)$ is strictly monotonically increasing with respect to $x_1,x_2,\ldots,x_m$, and x_{m+1}, x_{m+2} $,\ldots,x_n$ is strictly monotonically decreasing for x_{m+1}, then the inverse uncertainty distribution of the uncertainty variable $f(\xi_1,\xi_2,\ldots,\xi n)$ is:

$$\Phi^{-1}(\beta)=f^{-1}\left(\Phi_1^{-1}(\beta),\Phi_2^{-1}(\beta),\ldots,\Phi_m^{-1}(\beta),\Phi_{m+1}^{-1}(\beta),\ldots,\Phi_n^{-1}(\beta)\right) \tag{7}$$

2.2 Cutterhead Belief Reliability Modeling

2.2.1 Determination of Cutterhead Master Performance Indicators and Thresholds.

The main function of TBM cutter head is rock breaking excavation, and the excavation performance parameters representing the excavation function mainly include mean velocity *v*, rotational speed *n*, penetration *λ*. Considering the comprehensive impact of various uncertain factors during the TBM excavation construction process, penetration is selected as the main performance indicator of the cutterhead. Excessive penetration of the cutterhead during excavation can lead to overload of the cutterhead excavation load and damage to construction machinery. Using it as the main performance indicator can intuitively explain the performance of cutterhead excavation, and also demonstrate the coupling effect of excavation operation parameters, rock parameters, and cutterhead structural parameters. Compare the secondary excavation performance indicators with the main performance indicators based on the speed and average excavation speed of the cutterhead.

Due to the uncertain factors such as the type of surrounding rock, the distribution of surrounding rock and the level of operation, the higher the penetration threshold is, the lower the misjudgement rate is. Therefore, the maximum of each kind of critical value is taken as the lower bound of the penetration threshold, and the critical minimum value is taken as the parameter of the penetration to set the upper bound.

$$\inf\left(\vee\left(\lambda_{th,o_i}\right),\lambda_{th,s}\right)\le\lambda_{th}\le\sup\left(\wedge\left(\lambda_{th,o_i}\right),\lambda_{th,s}\right)\quad i=1,2,3\ldots n \tag{8}$$

In the formula, $\lambda_{th,\,S}$ is the subjective threshold and $\lambda_{th,\,O}$ is the objective threshold.

2.2.2 Cutter Disc Performance Analysis.

The factors that influence the driving performance of the cutter head include the internal factors x (such as the thrust of the cutter head, material, technology, etc.) and the external factors y (such as compressive strength, integrity, working stress, etc.). In the process of TBM cutter head driving, the internal and external factors that affect the driving performance are the equipment parameters, rock mass index and driving parameters. The common equipment parameters include the cutter head radius, the cutter head maximum propulsion power, the cutter head system maximum torque and so on.

Because of the complex coupling of the factors affecting the driving performance of the cutter head, the insufficient data samples or incomplete knowledge will lead to the uncertainty of the parameters.

2.2.3 The Establishment of Penetration Equation of Cutter Head.

Because the thrust acts on the surrounding rock directly, when the thrust exceeds the compressive strength of the surrounding rock, the rock will be destroyed. There must be a corresponding relationship between TBM tunneling rate and thrust and surrounding rock parameters. A study by the Norwegian University of Science and technology shows [14]:

$$\lambda = \left(\frac{\mathrm{F}}{F_1} \right)^{\alpha} \tag{9}$$

In the formula: λ is the penetration degree of the cutter head, representing the rate of the cutter head driving, whose magnitude is mainly influenced by the equipment factor and the surrounding rock geological factor; F is the thrust of the cutter head, the friction between the shield shell and the wall of the tunnel and the tensile force of the subsequent supporting facilities are ignored; F_l is the thrust of the cutter head when the penetration is equal to 1 mm · rev^{-1}; α is the coefficient of penetration of the cutter head, it is mainly affected by the strength and integrity of surrounding rock.

The regression analysis method is an important method for domestic and foreign scholars to study the operation rule of TBM cutter head, and can deeply excavate the correlation among various factors.

The uniaxial compressive strength and integrity coefficient of rock extracted from the field are independent variables, and the thrust and penetration coefficient of cutter head are dependent variables. The linear regression model is established according to the data of each parameter after linearization, see formula (10).

$$\begin{cases} F_1 = A_0 + A_1 R_c + A_2 K_v \\ \alpha = B_0 + B_1 R_c + B_2 K_v \end{cases} \tag{10}$$

In formula A_0, A_1 and A_2 are constant terms of thrust f 1 for calculating unit cutter head penetration and linear regression coefficients of R_C and K_V, B_0, B_1, B_2 is the constant term for calculating the cutter head invasion coefficient α and the linear regression coefficients for R_C and K_V.

2.2.4 The Establishment of Cutter Head Margin Equation.

In the theory of assured reliability, the distribution of performance margin depends on the comprehensive effect of influencing factors. Generally, according to the different parameters, it can be expressed as the following three cases, The performance margin M can be expressed as:

$$M = d\left(\lambda, \lambda_{th}\right) = \begin{cases} \lambda - \lambda_{th} & \lambda \le \lambda_{\mathrm{th}} \\ \lambda_{th} - \lambda & \lambda \ge \lambda_{\mathrm{th}} \\ \min\left(\lambda - \lambda_{th,L},\ \lambda_{th,T} - \lambda\right) & \text{uncertainty} \end{cases} \tag{11}$$

In order to make the margin more able to reflect the working state of the cutter head, the point closest to the critical value is selected when calculating the threshold value, it makes the margin in the reliability evaluation process have the maximum statistical efficiency or the minimum misjudgment rate. Combining formula (8) further establishes the performance margin equation:

$$\begin{aligned} M &= \min(\lambda - \lambda_{th,L}, \lambda_{\mathrm{th,T}} - \lambda) \\ &= \min\{\lambda - \max\left(\vee\left(\lambda_{th,o_i}\right), \lambda_{th,s}\right), \min\left(\wedge\left(\lambda_{th,o_i}\right), \lambda_{th,s}\right) - \lambda\} \quad i = 1,2,3 \ldots n \end{aligned} \tag{12}$$

In the formula, $\lambda_{\mathrm{th,\,L}}$ is the lower definite bound; $\lambda_{\mathrm{th,\,T}}$ is the upper definite bound.

2.2.5 The Establishment of the Cutter Head Reliability Measurement Equation.

It is necessary to analyze the parameter of uncertainty of penetration when establishing the TBM cutter head reliability model. For small sample data, we can use uncertain estimation and expert experience to determine the distribution parameters. In this paper, the uncertain distribution type is obtained according to the experience and data law. The distribution parameters are calculated according to the maximum likelihood method.

The inverse function can be used for numerical integration calculations. According to definition 3(algorithm), Formula (4) can be expressed as follows:

$$\begin{aligned} R_B &= \mu\left\{\min\left(d\left(\left(\lambda_{th,L}, \lambda_{th,T}\right), \lambda\right)\right) + \Phi_{\varepsilon}\left(\Delta\lambda\right) > 0\right\} \\ &= \beta_1 \left|\min\left\{\Phi^{-1}_{\lambda_{th}}\left(\beta_1\right) = \Phi^{-1}_{\lambda}\left(1 - \beta_1\right)\right\}\right. + \beta_2 \end{aligned} \tag{13}$$

In the formula, R_B is confidence reliability, μ is probability measure, β_1 is confidence reliability value affected by uncertainty factors, β_2 is reliability affected by random interference term. $\Phi^{-1}(x)$ is an inverse uncertain distribution function For the random disturbance term, the confidence reliability B_2 under the influence can be deduced by using the uncertainty theory and the chance theory.

$$\beta_2 = \int_{-\infty}^{+\infty} \Phi'_{\varepsilon}\left(\Delta\lambda\right) dF \tag{14}$$

3 ACTUAL CASES

3.1 Project and Equipment Profile

Taking the TBM construction of a certain bid section of a water diversion tunnel project in northern Xinjiang as an actual case, the tunnel mainly passes through the late Warwickshire intrusive gneiss granite with a total length of 23.55 km. The surrounding rock conditions of the tunnel are generally good, most of which are of Class II and III, the compressive strength is 30 ~ 170 MPa, which is medium-hard and hard rock with good overall stability. The section DK36+75.63 ~ DK49+994.38 is constructed with the open type TBM made by medium iron equipment. The maximum allowable thrust is 27488 KN and the maximum torque is 12525 KN·m. The maximum penetration is 30mm·rev^{-1}, the maximum rotation speed of cutter head is 6.8 r·min^{-1}, and the maximum tunneling speed is 52mm·min^{-1}.

3.2 Cutter Head Reliability Calculation

Select 7 groups of mileage points with the highest frequency of lithology in section DK36+75.63~DK4 9+994.38, and their excavation parameters are shown in Table 1. The data listed in the table are all data from the normal wear and operation status of the excavation machine's cutting tools.

Table 1. TBM tunneling parameters table

Mileage	Rock compressive strength R_c/Mpa	Integrity coefficient K_v	Unit penetration thrust F_l/KN	The coefficient of penetration α
DK37+085	156.3	0.737	10 418.09	2.178
DK37+759	95.1	0.647	10 823.81	2.216
DK48+641	103.3	0.731	8 776.91	2.254
DK48+736	93	0.642	8 929.90	2.275
DK49+937	46.5	0.47	3 755.66	2.474
DK49+961	38	0.32	3 213.24	2.569
DK49+969	57.1	0.397	4 357.56	2.451

Use the Curve Fitting toolbox in Matlab to process and analyze the 2-5 graphs. From the fitting curve in the figure, it can be seen that there is a close correlation between the uniaxial compressive strength of rocks, rock integrity coefficient, unit penetration thrust, and cutterhead intrusion coefficient. Assuming the cutterhead thrust is a constant value, F_l increases with the increase of rock uniaxial compressive strength Rc and rock integrity coefficient Kv, while α It will decrease with the increase of rock strength and integrity coefficient, and with the improvement of rock mass quality, the penetration of the cutterhead will decrease, which is consistent with practical experience. its fitting situation is shown in Figure 1-4.

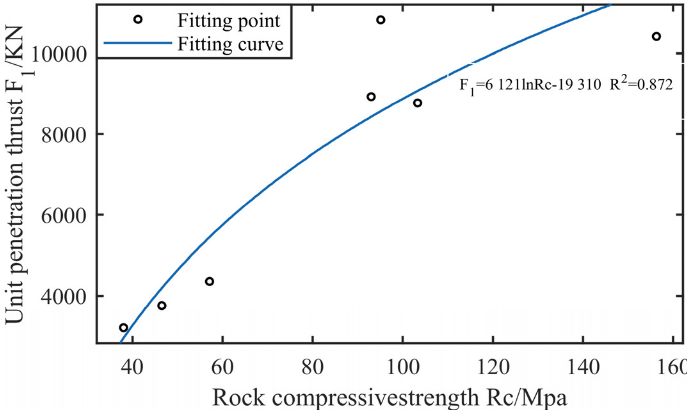

Fig. 1. F_1-Rc parameter change diagram

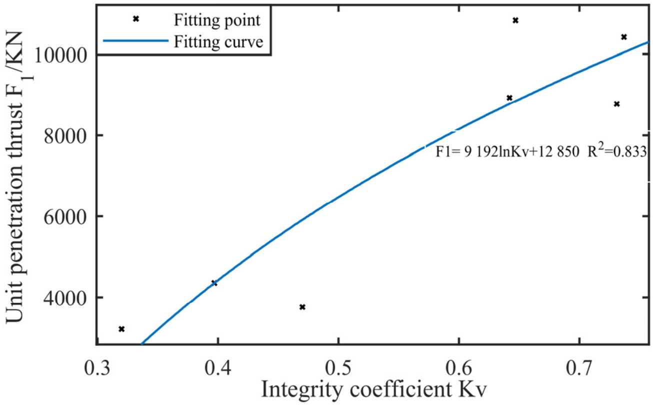

Fig. 2. F_1-Kv parameter change diagram

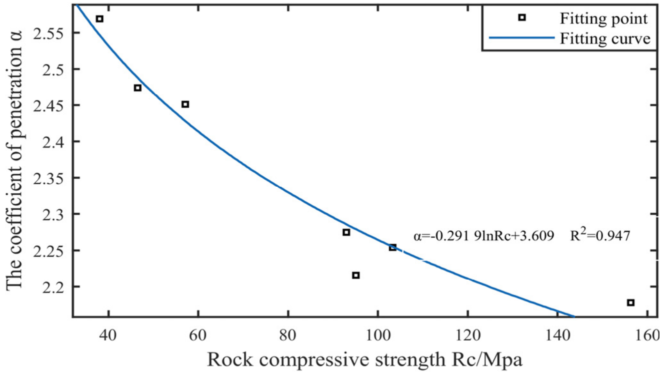

Fig. 3. α-Rc parameter change diagram

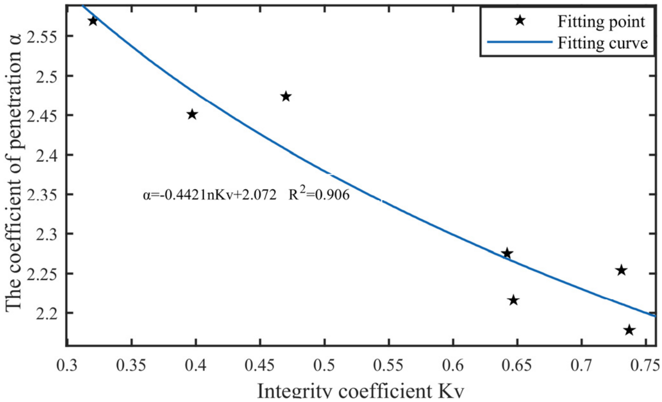

Fig. 4. α-Kv parameter change diagram

Among them, R^2 is the fitting similarity index, and the closer R^2 is to 1, the more accurate the fitting function is. After fitting with the binary regression model, a normalized model with only significant terms was obtained at a 95% confidence level through the square difference homogeneity test (F-test), with R^2 of 0.887 and 0.9698, respectively. Based on equation (9), the equation for calculating the penetration of this type of cutterhead can be expressed as:

$$\lambda = \left(\frac{F}{4\ 114.15\ln Rc + 3\ 321.12\ln Kv - 8094.27} \right)^{-0.177\ 9\ln Rc - 0.188\ 6\ln Kv + 2.999} \tag{15}$$

According to the "*GBT50218-2014 Engineering Rock Grading Standard*" [15], the maximum uniaxial compressive strength Rc and maximum integrity coefficient K_V of Class II and III rock masses are 170Mpa and 0.75. According to equation (8), the lower limit of the penetration threshold for the TBM cutter head of this model is 5.81 mm • rev^{-1}, and the upper limit of the penetration threshold is 30 mm • rev^{-1}.Scholars have pointed out through extensive data analysis that the TBM cutter head exhibits an approximate normal distribution relationship among various excavation parameters within each excavation cycle. Consider the lower limit distribution of the penetration threshold as a normal uncertainty distribution. Using the minimum value of the penetration threshold as the mean, the standard deviation of the normal uncertainty distribution is obtained using the maximum likelihood estimation method, as shown in Table 2.

The uncertainty analysis of the influencing factors of the main performance indicators includes the inherent uncertainty of surrounding rock and the cognitive uncertainty of random interference terms. The inherent uncertainty of uniaxial compressive strength mainly comes from the development of rock mass, and the inherent uncertainty of integrity coefficient mainly comes from the distribution of rock mass structure. Introduced here Φε Make corrections and assume a normal random distribution, $\Phi\varepsilon \sim N(\mu, \sigma^2)$. The distribution and parameter types of each uncertain parameter in the formula are shown in Table 2.

Table 2. Uncertainty distribution of each parameter

Parameters	Satisfying a distribution
random disturbance term Φε	N(0, 0.7^2)
F/KN	N(14 583.9 4049.5)
F_l/KN	N (8 987.1,709.69)
α	N(2.282 0.034)
$\lambda_{th,L}/(mm\cdot rev^{-1})$	N (5.81, 0.16)
$\lambda_{th,T}/(mm\cdot rev^{-1})$	30

Table 3. Reliability results with different parameter distributions

Distribution	R_B
F=14 583.9, λ_{th}=5.81	0.998 5
F=14 583.9, λ_{th}~N(5.81,0.16)	0.996 5
F~N(14 583.9,4 049.5), λ_{th}=5.81	0.960 2

Due to the joint influence of parameter uncertainty distribution on the main performance indicators of the cutterhead, its analytical solution cannot be obtained under the influence of random interference terms. Therefore, numerical solutions are used to calculate reliability. Combining equations (13) and (14), Matlab is used to solve the reliability of the cutterhead under different parameter distributions. The calculation results are shown in Table 3.

From the above results, it can be seen that when considering uncertainty, the greater the uncertainty of the parameters, the greater the impact on the reliability of the TBM cutter head system, and the reliability of the cutter head shows a decreasing trend. In addition, during the construction and excavation process, the inherent uncertainty of thrust in the face of changes in surrounding rock results in a greater degradation of the reliability of the cutterhead due to its influence than the result of only considering the uncertainty of the penetration threshold. This indicates that the uncertainty of cutterhead thrust is greater than the uncertainty of the cutterhead penetration threshold, and the reliability of the cutterhead decreases from 0.998 5 to 0.960 2, with a more obvious trend.

In the actual excavation process, TBM drivers usually considering mean velocity *v*, rotational speed *n*, penetration *λ*. Based on this, the degree of influence of different parameter uncertainties on the reliability curve is studied, as shown in Figure 5.

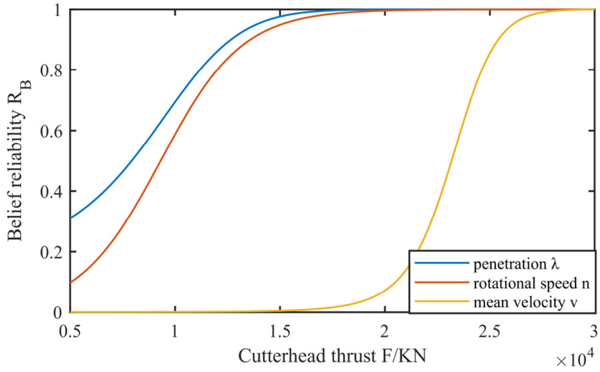

Fig. 5. The reliability of different performance indica-tors changes with the thrust of the cutterhead

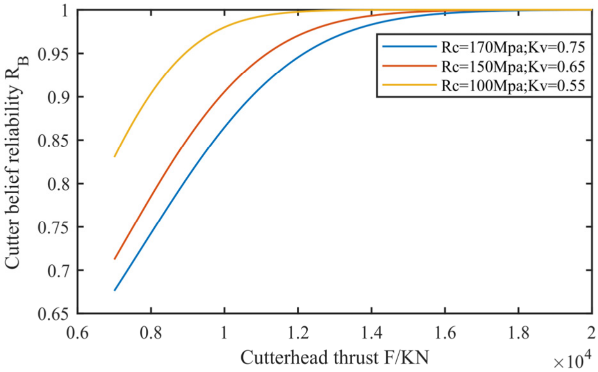

Fig. 6. Reliability variation curve with tooling thrust under consideration of parameter uncertainty

It can be found that when considering the main performance indicators of cutterhead speed and penetration, the reliable point position of the reliability curve is close to the smooth trend, indicating that the influence of cutterhead speed and penetration as performance indicators on cutterhead reliability is the most sensitive. However, the speed of the cutterhead exhibits a disadvantage of rapid reliability development compared to the penetration rate, which makes it unable to effectively demonstrate the reliability of cutterhead excavation. Therefore, it is relatively appropriate to choose the penetration rate as the main performance indicator to study the cutterhead excavation performance.

Based on the above analysis, the reliability of TBM excavation can be improved by focusing on controlling the uncertainty of penetration and cutterhead thrust. Therefore, the reliability of the cutterhead excavation process can be increased by controlling the cutterhead thrust. Figure 6 shows the changes in the thrust and reliability of the TBM cutterhead under different rock characteristics analyzed. In the TBM construction of this section, when the thrust of the cutterhead is controlled above 12 195KN, the reliability of the cutterhead remains above 95%. When faced with inherent uncertainty and cognitive uncertainty factors, adjusting the cutterhead thrust to above 17 643KN can ensure the smooth progress of the excavation process from the perspective of reliability. Based on the construction report in actual engineering, it can be seen that the driver did not experience any shutdown faults during the TBM cutter head thrust range of 12 000~17 600 KN. The TBM cutter head operates relatively reliably, and the inference results of the theoretical model are in good agreement with the actual situation.

4 CONCLUSION

This article proposes a reliability measurement method for TBM cutterhead system based on belief reliability in engineering practice. By establishing a cutterhead penetration equation, the TBM cutterhead excavation performance is quantitatively measured, and the cognitive uncertainty is quantified to complete the belief reliability calculation of TBM cutterhead. The main research conclusions are as follows:

(1) The steps of applying the reliability theory of certainty to the reliability research of TBM cutterhead are proposed, and the cutterhead penetration is selected as the cutterhead excavation performance index. TBM cutterhead reliability model is constructed, which realizes the calculation of cutterhead reliability considering cognitive uncertainty factors such as model uncertainty, influencing factor uncertainty, and parameter distribution uncertainty.

(2) The TBM cutter head is affected by various uncertain factors during the excavation process, resulting in varying degrees of degradation in its reliability. By exploring the relevant effects of the main rock mass indicators on the cutterhead invasion coefficient and unit penetration thrust, the calculation method of the main performance indicators is obtained.

(3) Taking the North Xinjiang Water Supply Tunnel project as an example, a quantitative study was conducted on the inherent uncertainty of cutterhead thrust and the cognitive uncertainty of penetration threshold. A reasonable range of cutterhead thrust was proposed to ensure the reliability of the cutterhead excavation process, and the calculation results were in good agreement with the actual engineering situation.

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