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Original scientific paper

A Method for Analyzing Correlation Grades of Factors Influencing the Behavior of Bolted Connections Based on the Grey Correlation Degree

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Abstract: Failure caused by loosening of bolted connections is a common problem in practice. To reasonably optimize the factors influencing the behavior of bolted connections, this paper proposed a method for analyzing the correlation grades of factors influencing the behavior of bolted connection based on the grey correlation degree. First, Deng's correlation degree is optimized from three different perspectives: dimensionless factors, resolution coefficient, and weight assignment. Then, a model of the bolted connection is established based on the degrees of correlation of influencing factors. To avoid inverse correlation of influencing factors caused by fluctuation of the residual preload, a difference classification method based on qualitative analysis is proposed. By grading the correlation degree of each influencing factor, optimal selection of parameters in bolted connections can be achieved. Finally, the bolted connection on a third-rail current collector slide was taken as an example and residual preload analysis was performed. It can be concluded that reasonably selecting the bolt material and size and optimizing the friction condition of various contact surfaces is necessary to effectively improve the reliability of the bolted connection. The method was verified by simulations.

Keywords: bolt connection; correlation grade analysis method; difference classification method; grey correlation degree; third-rail current collector slide

1 INTRODUCTION

Bolted connections, as common fasteners, are widely used, for example, in trains, buildings, and aircraft, mainly owing to their easy mounting, convenient assembly, and reliable performance [1, 2]. However, bolted connections are often exposed to vibrations throughout their service life, and are thus susceptible to loosening, fracture, and other forms of failure. For this reason, factors influencing the behavior of bolted connections should be optimized to improve their reliability.

Scholars both at home and abroad have explored the relationship between influencing factors and reliability using three different approaches: theoretical analysis, simulation, and experiments. In terms of theory, Hou [3] established a one-dimensional (1D) mathematical model of a bolt that considers elastoplasticity and creep effects, and analyzed the variation in stress, strain, and tension in the threads with temperature. Vingradov and Huang [4] introduced a dynamic model of a bolted connection and showed that high-frequency vibrations can lead to loosening of the bolted connections.

In the area of simulations, Yang [5] built a finite element model of a bolted connection with a metal housing and comparatively analyzed the stresses in bolts with and without a bolt fixing structure. The presence of a bolt fixing structure resulted in a more reasonable stress distribution in the bolt. Ren [6] developed a finite element model of the propulsion shafting system of a container ship and investigated the relationship between the number of bolts and shafting vibration. The results suggest resonance amplitude, assembly/disassembly, and other practical issues should be comprehensively considered in selecting the appropriate number of bolts. Wang [7] developed a finite element model of a bolt under lateral excitation and analyzed the effects of initial preload and coefficient of friction on the loosening mechanism of the bolt. Yang [8] introduced a parametric three-dimensional (3D) finite element model for bolted connections and analyzed the mechanical properties of connections containing bolts of various pitches and different numbers of threads.

On the experimental front, Junker [9] introduced the Junker looseness tester and found that compared to an axial load of the same magnitude, the dynamic lateral load more easily leads to loosening of bolted connections [10]. Yang tested the double-nut bolts used in transmission towers under lateral vibration and showed that an ordinary double-nut bolted connection is more reliable when the mounting torque of the lower nut is 25% of the upper nut mounting torque.

Based on the above review of the literature, to date, studies have only focused on the influence of relevant factors on the reliability of bolted connections, whereas the degree of correlation of multiple influencing factors and the reliability of bolted connections have not been considered. This paper presents a method for analyzing the correlation grades of factors influencing the behavior of bolted connection based on grey system theory. Factors influencing the reliability of bolted connections can be classified and graded, which not only allows inversion of the correlation order of influencing factors caused by fluctuation of the residual preload to be avoided, but also optimizes the influencing factors in a targeted manner. First, on the basis of Deng's correlation degree, optimization is performed from three perspectives, that is, dimensionless processing of factors, resolution coefficients, and weight assignments. Then, the difference classification method based on qualitative analysis is introduced and combined with grey correlation degree analysis to develop a method for analyzing the correlation grade factors influencing the behavior of bolted connections, which can be used in qualitative analyses. Finally, to verify the proposed method, correlation grades of factors influencing the behavior of bolted connections on a third-rail current collector slide were analyzed.

2 GREY CORRELATION DEGREE

Grey system theory [11] does not require massive experimental datasets or prior probability distributions and has therefore become widely used in the fields of management and engineering [12, 13]. However, grey correlation analysis is rarely applied to analyze mechanical parts, especially bolted connections. The grey correlation degree is an essential component of grey system theory and reflects the degree of correlation between an event and an influencing factor. The judgment is based on the similarity degree between the curve of the event data sequence and the curve of the data sequence of the influencing factor. A higher similarity degree between two curves suggests a higher correlation between the event and influencing factor; and vice versa.

Depending on the structure and mechanism, correlation degrees can be classified as follows: Deng's correlation degree, absolute correlation degree, relative correlation degree, slope correlation degree, T-type correlation degree, B-type correlation degree, C-type correlation degree, etc.

In this paper, the grey correlation degree, based on both Deng's correlation degree and the relative correlation degree, is introduced.

The data sequence of an influencing factor can be defined as where i denotes the number of influencing factors, i = 1, 2,…, n; k is the index number; $x_i(k)$ is the observed data of influencing factor X_i relative to the k^{th} index.

The event data sequence can be defined as

$$X_i = \left(x_i(1), x_i(2), \cdots, x_i(k), \cdots, x_i(n)\right) \tag{1}$$

where $y_j(k)$ is the observed data of data sequence Y_j relative to the k^{th} index.

$$Y_j = \left(y_j(1), y_j(2), \cdots, y_j(k), \cdots, y_j(n)\right) \tag{2}$$

2.1 Deng's Correlation Degree

An image conversion process is first performed to reduce the effects of differences among various data indices, in terms of both dimension and order, on the correlation degree calculation.

Assuming D is the sequential algorithm, then where $x_i(k)\cdot d = x_i(k)/x_i(1) \neq 0$

$$X_i' = X_i \cdot D = (x_i(1)\cdot d, x_i(2)\cdot d, \cdots, x_i(k)\cdot d, \cdots, x_i(n)\cdot d) \tag{3}$$

In this case, D is the initial-value operator and X_i' is the image of X_i under D (referred to as the initial-value image).

Data sequences X_i and Y_j undergo initial-value image conversion.

The difference sequence is defined as where Δ_{ij} = ($\Delta_{ij}(1)$, $\Delta_{ij}(2)$, …, $\Delta_{ij}(n)$)

$$\Delta_{ij}(k) = \left| x_i'(k) - y_j'(k) \right| \tag{4}$$

The maximum absolute difference and minimum absolute difference are defined as

The correlation coefficients of data sequences X_i and Y_j are

$$M_j = \max \Delta_{ij}(k),\ m_j = \min \Delta i_j(k) \tag{5}$$

$$\xi_{ij}(k) = \frac{m_j + \xi M_j}{\Delta ij + \xi M_j}, \xi \in (0,1] \tag{6}$$

where ξ is the resolution coefficient, which can change the difference between correlation coefficients, and is normally 0.5.

In this case, the initial-value correlation degree of data sequences X_i and Y_j is

2.2 Relative Correlation Degree

Initial-value images X_i' and Y_j' of X_i and Y_j can be obtained from Section 1.1. Assuming

$$\gamma_{ij} = \frac{1}{n}\sum_{k=1}^{n} \xi_{ij}(k),\ i = 1, 2, \cdots m \tag{7}$$

The relative correlation degree becomes

$$\left|S_i\right| = \left|\sum_{2}^{n-1} X_i'(k) + \frac{1}{2} X_i'(n)\right| \tag{8}$$

$$\left|S_j\right| = \left|\sum_{2}^{n-1} Y_j'(k) + \frac{1}{2} Y_j'(n)\right| \tag{9}$$

$$\left|S_i - S_j\right| = \left|\sum_{2}^{n-1} \left[X_i'(k) - Y_j'(k)\right] + \frac{1}{2} Y_j'(n) - \frac{1}{2} X_i'(n)\right| \tag{10}$$

2.3 Problems with Traditional Correlation Degrees

$$\gamma_{ij} = \frac{1 + \left|S_i\right| + \left|S_j\right|}{1 + \left|S_i\right| + \left|S_j\right| + \left|S_i - S_j\right|} \tag{11}$$

1) The resolution coefficient ξ in Deng's correlation degree affects the magnitude of the correlation degree and influences the correlation degrees of the influencing factors. The relative correlation degree calculation does not cover resolution coefficients and lacks judgment about the overall trend, and is therefore one-sided.

2) Traditional correlation degrees have not taken into account differences in the influence of various factors on the event. Different factors will have different weights and neglecting these weights can lead to significant deviation from reality.

3 METHOD FOR ANALYZING THE CORRELATION GRADES OF BOLTED CONNECTIONS

To address the difficulties in optimally selecting the various factors influencing the behavior of bolted connections, dimensionless processing of factors is introduced as the optimization method based on Deng's correlation degree. First, mean-value images of various data sequences are obtained. Then, coefficients with suitable resolutions are defined to acquire the correlation coefficients. Next, the objective weighting method and information entropy principle are used to assign weights to the influencing factors and the correlation degrees are calculated. Finally, the difference classification method is used to grade each correlation degree and commonalities among factors of the same grade are summarized. As such, the correlation degree between the reliability of the bolted connection and relevant influencing factors can be obtained according to their specific correlation grades, with the overall aim of identifying the optimal scheme.

3.1 Dimensionless Data Processing

Differences exist among factors influencing bolted connections in terms of both dimension and order of magnitude; therefore, dimensionless processing is necessary. Traditional correlation degrees can achieve initial-value processing of sequence data. However, data sequences of the influencing factors of bolted connections are random and without any definite time order, thus, data processing is required in this case. The mean value method is adopted and can be described as follows:

Where X_i' is the image of X_i under the mean-value operator, referred to as the mean-value image.

$$X_i' = X_i \cdot D = (x_i(1)\cdot d, x_i(2)\cdot d, ..., x_i(k)\cdot d, ..., x_i(n)\cdot d) \quad (12)$$

Where

$$x_i(k)\cdot d = \frac{x_i(k)}{\frac{i}{n}\sum_{k=1}^{n} x_i(k)} \quad (13)$$

3.2 Selection of Resolution Coefficients

In determining correlation degrees influencing factors of bolted connections, the magnitude of the resolution coefficient will have some effect on the results. According to Eq. (6), the product of resolution coefficient ξ and the maximum absolute difference have a significant effect on the correlation coefficients. To ensure the results are more aligned with reality, resolution coefficient ξ should meet the following basic criteria:

When sequence data values are stationary, the selected ξ value should enhance their discriminability, thereby embodying integrity.

2) When singular values exist among sequence data values, the selected ξ value should weaken the effects of singular values on correlation coefficients.

To meet these conditions, the following values should be assigned to resolution coefficient ξ:

1) When $M \ge \frac{3}{N}\sum_{i=1}^{N}\left|x_i'(k) - y'(k)\right|$, singular values exist among sequence data values. In this case, a small value should be assigned to resolution coefficient ξ within the interval $[\theta_i, 1.5\theta_i]$, thus weakening the effect of M on the correlation coefficients. Normally, the right endpoint of the interval is selected according to the monotonicity of the function, i.e., $1.5\theta_i$.

2) When $M \le \frac{3}{N}\sum_{i=1}^{N}\left|x_i'(k) - y'(k)\right|$, the sequence data values are stationary. In this case, a large value should be assigned to resolution coefficient ξ within the interval $[1.5\theta_i, 2\theta_i]$, thus enhancing the effect of M on the correlation coefficients, which is normally set to $2\theta_i$, where

$$\theta_i = \frac{3\sum_{i=1}^{N}\left|x_i'(k) - y'(k)\right|}{M \cdot N}.$$

3.3 Determination of Weights of Influencing Factors

In the analysis of correlation degrees of bolted connections, different influencing factors will have different weights. Assigning the same weight values would produce deviations in the correlation degree calculation. The weights assigned to different influencing factors should reflect their different roles. The main methods for determining the weights of influencing factors include the subjective weighting method and the objective weighting method. Considering the small effects of subjective factors on the factors influencing the behavior of bolted connections, the objective weighting method is adopted. More specifically, the entropy weight method is used to assign weight, thus overcoming the problems of traditional approaches to mean correlation degrees calculations. The specific steps of the calculation are as follows:

1) Calculate feature weight p_{ik} of the i^{th} influencing factor in the k^{th} bolted connection model:

$$p_{ik} = \frac{x_i'(k)}{\sum_{i=1}^{m} x_i'(k)} \quad (14)$$

2) Calculate entropy value h_k of the k^{th} bolted connection model:

$$h_k = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ik}\cdot \ln p_{ik} \quad (15)$$

3) Calculate weight value ω_k of the k^{th} bolted connection model:

$$\omega_k = \frac{1 - h_k}{n - \sum_{k=1}^{n} h_k} \quad (16)$$

4) Calculate the improved grey correlation degree:

$$\gamma_{ij} = \sum_{i=1}^{n} \xi_{ij}(k)\omega_k \quad (17)$$

3.4 Grading of Correlation Degree Based on Difference Classification

Bolted connections must remain stable under vibrations, however, their behavioral data sequences tend to fluctuate to some extent. For instance, a bolted connection in a stable state will have different residual preloads at different time points, which induce fluctuation in the correlation degrees and may cause inversion of the correlation matrix and compromise the accuracy of the results. To attain consistent conclusions, it is necessary to comparatively analyze correlation degrees by grading them based on difference classification.

The difference classification method grades correlation degrees according to their differences. A correlation difference (m) is introduced based on the differences between the overall correlation degrees. Influencing factors with the highest correlation degree are automatically classified as grade I; adjacent factors with a difference of less than m are classified into the same grade; a factor presenting a difference of greater than m from its adjacent factor is classified into the next grade. Thus, by parity of reasoning, influencing factors are classified into three correlation grades. A common solution is sought for all influencing factors within the same correlation grade.

4 EXAMPLE ANALYSIS

In this section, the correlation grades of influencing factors of the bolted connections on a third-rail current collector slide are analyzed to verify the proposed method.

4.1 Building of Third-Rail Current Collector Model

A third-rail current collector model and bolted connection model were established for the analysis. The third-rail current collector system is comprised of a fuse box, swing arms, current collector slides, and various other parts. A 3D model was built in CREO using the actual parameters of the system, then imported into ABAQUS for finite element analysis. The finite element model is shown in Fig. 1.

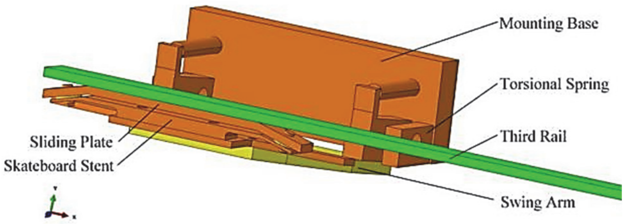

Figure 1 Finite element model of third-rail current collector

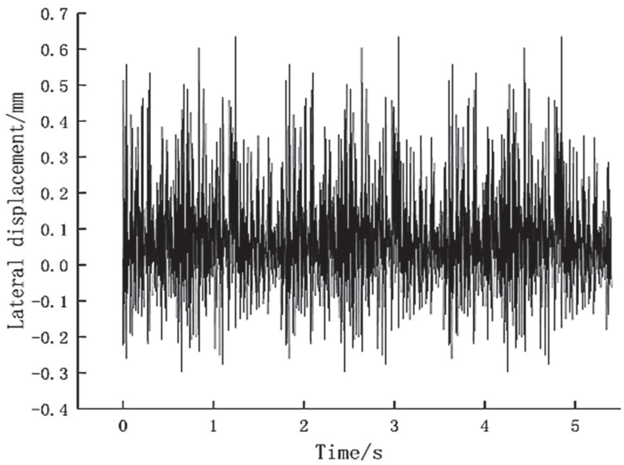

Figure 2 Time-displacement curve of lateral vibration of lower slide

During operation, trains are exposed to the random vibrations caused by track irregularities. In this study, the fifth grade American track spectrum was converted through time-frequency transformation into a time-displacement curve in MATLAB, and applied as the vibration excitation to the finite element model. A speed of 60 km/h, which is the optimal running speed of a third-rail train, was also adopted for the simulations and a lateral vibration time-displacement curve of the lower slide was obtained, as shown in Fig. 2.

The simulated lateral vibration excitation was adopted as the vibration excitation for precise modeling of the bolted connection.

4.2 Bolted Connection Model

Modeling of the bolted connection was carried out using the actual parameters of slide bolts. The model contained the lead angle, and was capable of precisely simulating the change in residual preload in the bolted connection. The bolts were distributed symmetrically on both sides of the slides. Only one bolt was analyzed. The slider shape was simplified and contact surfaces for applying the lateral vibration displacement were retained. Fig. 3 shows the precise, simplified finite element model of the bolted connection.

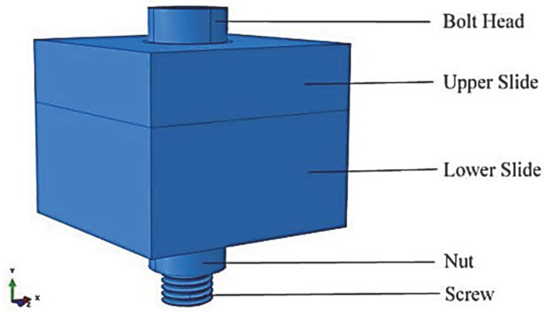

Figure 3 Finite element model of bolted connection

Contact pairs were arranged on the bolt head pressure-bearing surface, nut pressure-bearing surface, sliding contact surface, and thread engagement surface. A preload element was applied in the middle of the bolt bar, and its length was fixed to sustain the preload effect. Based on the actual operating conditions, the upper surface of the upper slide was fully constrained, the two sides, parallel to plane YOZ were constrained in the X-direction, and the two sides parallel to plane YOX were constrained in the Z-direction. On the lower slide, the two sides parallel to plane YOZ were constrained in the X-direction.

The two sides of the lower slide parallel to plane YOZ were constrained in the X direction. The sides of the lower slide parallel to plane YOX were applied with the vibration load input extracted in Section 4.1 in the Z-direction, followed by the finite element analysis and calculations.

4.3 Data Analysis

The results of the simulation model were used as data for further analysis. The 12 influencing factors of the bolted connection model and the residual preload results of the simulation analysis were taken as the study objects. For the convenience of analysis, the symbols and meanings used are shown in Tab. 1. Data values of influencing factors of 12 different bolted connection models are shown in Tab. 2. At time t, the residual preload is Y_j, j = 1, 2, 3, 4, 5, 6. The values of $Y_j(k)$ correspond to the residual preload values of the k^{th} bolted connection at 1 s, 1.2 s, 1.4 s, 1.6 s, 1.8 s, and 2 s, given in Tab. 3.

Table 1 Definition of symbols used in finite element model of bolted connection

X_1	Bolt nominal diameter
X_2	Bolt pitch
X_3	Screw length
X_4	Thread length
X_5	Bolt head height
X_6	Nut thickness
X_7	Bolt connection gap
X_8	Upper slide thickness
X_9	Lower slide thickness
X_{10}	Bolt and nut elastic modulus
X_{11}	Coefficient of friction of contact pair on thread engagement surface
X_{12}	Coefficient of friction of contact pair on bolt head and nut pressure-bearing surface
X_{13}	Coefficient of friction of contact pair on upper/lower slide pressure-bearing surface
Y_j	Residual preload value at time t

Table 2 Influencing factors values

k	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
1	10	1.5	60	26	6.4	8.4	0.6	25.3	12.7	210	0.15	0.2	0.13
2	12	1.75	65	30	7.5	10.8	0.4	16.8	23	200	0.1	0.18	0.22
3	14	1.85	70	24	8.8	12.8	0.5	17	30.8	190	0.08	0.25	0.12
4	16	2	78	29	10	14.8	0.3	27.2	26	220	0.22	0.17	0.11
5	18	2.25	85	42	11.5	15.8	0.55	11.3	36.8	230	0.12	0.19	0.3
6	20	2.5	95	46	12.5	18	0.9	34.9	26	240	0.29	0.14	0.23
7	22	2.6	100	50	14	19.4	0.5	31.1	42.4	260	0.16	0.27	0.31
8	24	2.8	105	54	15	21.5	0.7	35.3	17	170	0.09	0.23	0.15

Table 3 Residual preload value Y_j at time t

Time t	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
1	14717.8	14461.8	14281.8	14250.3	14257.6	13992.5
2	19471.6	19426.8	19439.1	19436.2	19448.3	19400.5
3	18088.8	17805.4	17734.7	17694.1	17659.8	17481.4
4	19654.7	20452.5	19606.4	19627.3	19600.3	19282.1
5	20070.4	20063.8	20114.6	20171.4	20126.9	20197.9
6	19986.2	21490.7	19620.1	19598.6	19547.2	19341.3
7	18639.2	18294.5	18136.7	18008.6	17858.2	17649.4
8	19966.7	19977.1	19995.7	20005.9	19943	19972.1

The mean value method was applied to the data sequences in Tab. 2 to obtain mean-value images, which were then used to solve the difference sequence, maximum absolute difference, and minimum absolute difference using Eq. (5). The judgment criteria presented in Section 3.2 were used to obtain the resolution coefficients of the sequence data. By determining the weights of the influencing factors, Eqs. (14) to (17) could then be used to solve for the weight values of the various bolt models and to acquire the correlation degrees between the various influencing factors and residual preload of the bolt at time t. The results are presented in Tab. 4.

Table 4 Correlation degree between influencing factors of bolted connections and bolt residual preload at time t

No.	1 s		1.2 s		1.4 s		1.6 s		1.8 s		2 s	
	Symbol	Correlation degree	Symbol	Correlation degree	Symbol	Correlation degree	Symbol	Correlation degree	Symbol	Correlation degree	Symbol	Correlation degree
1	X_{10}	0.7466	X_{10}	0.7335	X_{10}	0.7439	X_{10}	0.7517	X_{10}	0.7513	X_{10}	0.7793
2	X_3	0.7165	X_3	0.7313	X_3	0.7267	X_3	0.7363	X_3	0.7345	X_3	0.7714
3	X_2	0.7033	X_2	0.7172	X_2	0.7119	X_2	0.7211	X_2	0.7195	X_2	0.7541
4	X_5	0.6492	X_4	0.6553	X_5	0.6614	X_5	0.6692	X_5	0.6682	X_5	0.6974
5	X_1	0.6474	X_1	0.6517	X_1	0.6516	X_4	0.6596	X_4	0.6585	X_4	0.6887
6	X_6	0.6465	X_6	0.6504	X_4	0.6516	X_1	0.6594	X_1	0.6584	X_6	0.6885
7	X_4	0.6463	X_5	0.6463	X_6	0.6510	X_6	0.6590	X_6	0.6579	X_1	0.6879
8	X_{12}	0.5891	X_7	0.5727	X_{12}	0.5948	X_{12}	0.6026	X_{12}	0.6024	X_{12}	0.6315
9	X_7	0.5752	X_{12}	0.5500	X_7	0.5855	X_7	0.5946	X_7	0.5955	X_7	0.6224
10	X_9	0.5446	X_{13}	0.5005	X_9	0.5520	X_9	0.5599	X_9	0.5597	X_9	0.5902
11	X_{13}	0.4964	X_9	0.4968	X_{13}	0.5078	X_{13}	0.5160	X_{13}	0.5160	X_{13}	0.5431
12	X_8	0.4940	X_8	0.4938	X_8	0.5042	X_8	0.5125	X_8	0.5130	X_8	0.5320
13	X_{11}	0.4286	X_{11}	0.4104	X_{11}	0.4296	X_{11}	0.4348	X_{11}	0.4348	X_{11}	0.4498

4.4 Grading of Correlation Degree Based on Difference Classification

According to the order of six groups of correlation degrees in Tab. 4, when correlation difference m is 5%, the influencing factors are clearly graded. Thus, correlation difference m was set as 5% for the difference classification of correlation degree. Tab. 5 presents the correlation grades of the influencing factors.

Table 5 Correlation grades of influencing factors

Correlation grade	Influencing factor
First correlation grade	X_{10}, X_3, X_2
Second correlation grade	X_5, X_1, X_6, X_4
Third correlation grade	X_{12}, X_7, X_9, X_8, X_{13}, X_{11}

From Tab. 5, the first correlation grade contains the elastic modulus of the bolt, screw length, and bolt pitch. Elastic modulus is a measure of the bolt's resistance to elastic deformation and a basic material property; therefore, it is important to select a suitable bolt material. Screw length is related to the thickness of the connected part, and should be minimized under the premise of maintaining reliability of the bolted connection.

The second correlation grade contained bolt head height, bolt nominal diameter, nut thickness, and thread length, all of which are basic parameters of standard bolts. Therefore, to strengthen the reliability of the bolted connection, choosing a suitable bolt is vital.

The third correlation grade covers the coefficient of friction of the contact pair on the bolt head and nut pressure-bearing surface, bolt connection gap, lower slide thickness, coefficient of friction of the contact pair on the upper/lower slide pressure-bearing surface, upper slide thickness, and coefficient of friction of the contact pair on the thread engagement surface. All of these are environmental factors related to both the operating state and operating environment.

Analysis of the above three correlation grades reveals that the key to strengthening the reliability of bolted connections lies in selecting a suitable bolt material and size. After a suitable bolt size is selected, the next step is to properly adjust the friction conditions of the contact surfaces.

4.5 Simulation Verification

The correlation degrees of the bolted connection were verified using the control variable method. A bolted connection model was established according to the actual size of the M14 bolts on a third-rail current collector slide. Bolt sizes are specified in national standards and cannot be arbitrarily modified. Thus, for the bolt connection model, the elastic modulus of the bolt material X_{10}, coefficient of friction of the contact pair on the upper/lower slide pressure-bearing surface X_{13}, coefficient of friction of the contact pair on the thread engagement surface X_{11}, and coefficient of friction of the contact pair on the bolt head and nut pressure-bearing surface X_{12} were varied by 10% while all other parameters remained unchanged in order to compare the magnitude of their effects on the residual preload. Fig. 4 shows the changes in the ratio of residual preload to initial preload with vibration time as certain parameters are varied.

From Fig. 4, it can be observed that when vibration time is in the range of 1 s to 2 s, the residual preload ratios can be ranked in descending order as follows: $X_{10} > X_{12} > X_{13} > X_{11}$. The correlation order varies with time, however, as shown in Tab. 4, in the order of six groups of correlation degrees under analysis, influencing factors X_{10}, X_{11}, X_{12}, and X_{13} present the same order as X_{10}, X_{12}, X_{13} and X_{11} in descending order of correlation degree. This is consistent with the conclusions drawn from Fig. 4, and verifies the reliability of the method for analyzing the degree correlation between influencing factors and behavior of bolted connections. In addition, reasonableness of the method for analyzing the correlation grades of bolted connections was confirmed.

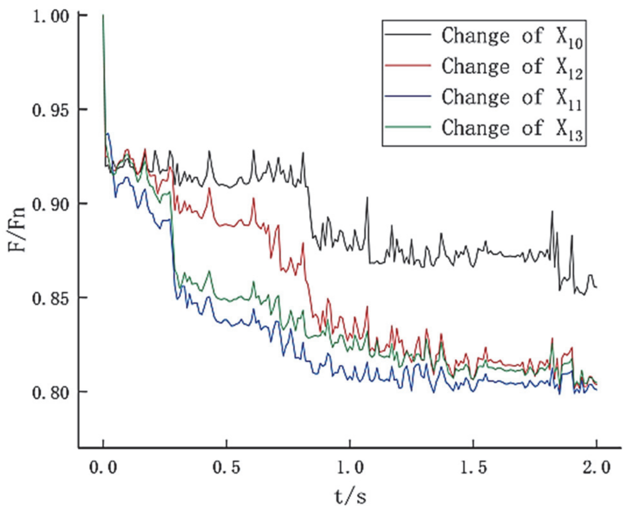

Figure 4 Change in residual preload with variation of parameters

5 CONCLUSIONS

1) The method for analyzing the correlation grades of influencing factors of bolted connections can be used to analyze multiple influencing factors at the same time, thus simplifying the analytical process.

2) The proposed method based on grey correlation degree analysis resulted in improvements in three key areas: dimensionless processing of factors, resolution coefficients, and weight assignment. The method can also be combined with the difference classification method for grading correlation degrees. A qualitative analysis was performed on factors of the same grade regardless of the magnitudes of correlation degree. This approach optimizes the selection of influencing factors in a targeted manner, avoids the adverse influence of variable correlation orders due to slight changes in differences, and achieves reasonable results.

3) The bolted connections on a third-rail current collector slide were taken as an example. It was found that to strengthen the reliability of bolted connections, it is necessary to first select a suitable bolt material and size, and then to optimize the friction conditions of various contact surfaces. Finally, the reliability of the proposed method was verified.

Acknowledgments

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