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Reliability-centered Maintenance Method and Its Application in a Tunnel

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Abstract: This study is performed in view of the current tunnel monitoring maintenance status and existing problems, and proposes the reliability-centered maintenance (RCM) as a maintenance concept. RCM can be introduced into tunnel management. Accordingly, a preliminary study on the application of the RCM method in tunnel monitoring maintenance is performed through the tunnel equipment failure mode and a reliability analysis. Finally, by adopting a case, this study shows that a tunnel using the RCM analysis method can effectively reduce the maintenance cost, and has certain economic and social benefits.

Keywords: tunnel; reliability; maintenance; monitoring; failure analysis

1 Introduction

With the rapid economic development, the demand for traffic in China is increasing daily. Meanwhile, the requirement for traffic safety has become more stringent, and new transport infrastructure is increasing significantly. In view of the severe situation of China's geography, tunnels have become the primary direction in transportation development. With the continuous development in science and technology, the modernized engineering structure is evolving and becoming more complex, and the function is becoming more refined. However, many structures are still facing unavoidable impediments in the development process [1]. Especially in recent years, the aging of tunnels has been highlighted. Frequent traffic accidents and natural destructions have increased the equipment failure rate, which has hindered the normal operation of the tunnel. Currently, the traditional maintenance method often leads to the unreasonable use of personnel and resources, which brings great economic loss to the maintenance of engineering structures. China is changing from a large-scale construction mode to a large-scale maintenance mode; therefore, the maintenance and management of the tunnel has become an important problem in tunnel engineering.

2 Basic views and advantages of RCM

2.1 Generation and basic meaning of RCM

We can divide the maintenance into three periods: the first period is primarily based on functional failure repair; the second period is primarily focused on maintenance plan and arrangement; the third period is about preventing, monitoring, and avoiding failure. The maintenance of the third period began around the 1970s, at which people have changed their understanding of the failure pattern. Numerous studies [2–4] have found that the probability of conditional failure related with time is approximately 11%, while the remaining 89% are independent of time. This means that time-based maintenance does not refine and handle most of the failure modes. This conclusion directly challenges the traditional notion about "handling failures in time and relying entirely on preventive maintenance regular-

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ly," and stimulates the birth of new maintenance concepts and optimization technologies simultaneously.

Reliability-centered maintenance (RCM) is a representative maintenance mode [5–7] of the third period. This maintenance concept originated from the civil aviation industry of the United States and has existed for more than half a century, and its definition is different in different fields. However, the most important and basic definition is that RCM is a process to determine the maintenance requirements of tangible assets when used. Therefore, it is an analytical method of making decisions. RCM is based on the risk analysis and reliability method in failure mode and failure consequences as the primary basis of maintenance strategy, with minimal resource consumption, using logical decision analysis methods to determine the content and methods of maintenance, and to develop the preventive maintenance program to achieve optimization and prolong the service life.

2.2 Advantages of RCM

2.2.1 Comparison with traditional maintenance methods

As an optimized maintenance strategy, the concept and principle of RCM are systematized, and can provide scientific guidance for the development of modern enterprise equipment. Significant differences exist in the concept and application compared with traditional maintenance methods, as shown in Table 1.

2.2.2 Comparison with other maintenance strategies

Different levels of understanding on the cause of equipment failure and its consequences will correspond to different maintenance methods, as shown in Fig. 1. For the equipment failure (mode, phenomenon, probability), if the possible fault causes and consequences are unclear, only restoration (BM) and regular maintenance (TBM) can be performed; if the monitoring or regular inspection of the equipment condition and change trend can be realized, the state maintenance (CBM) can be implemented; if the probability and consequences of the fault is known, RCM can be used; and if the fault mechanism and the initial reason of fault can be mastered, we can take the initiative to repair and carry out the radical maintenance (RM).

3 Current situation of tunnel maintenance

As the primary artery of our economy, the railway has been

Table 1. RCM contrast with traditional maintenance method.

Traditional maintenance	RCM maintenance	Note
The service time of equipment directly leads to equipment failure, so it is available to maintain the equipment regularly according to the service time	Equipment or system failure, degradation, and use time do not necessarily have a direct relationship; regularly scheduled maintenance is not necessarily good	Complex and simple equipment are significantly different from each other
Preventive maintenance can improve the inherent reliability.	Preventive maintenance cannot improve the inherent reliability	Reliability is the equipment- or product-inherent attributes
There is no concept of hidden faults and multiple faults	Based on the principle of reliability and the historical experience, or can eliminate hidden troubles to prevent multiple failures	This is one of the bases of reliability theory
By upgrading to improve the equipment performance	By improving the use and maintenance, similar effects can be achieved on the functions	Economy is also a consideration for basic maintenance

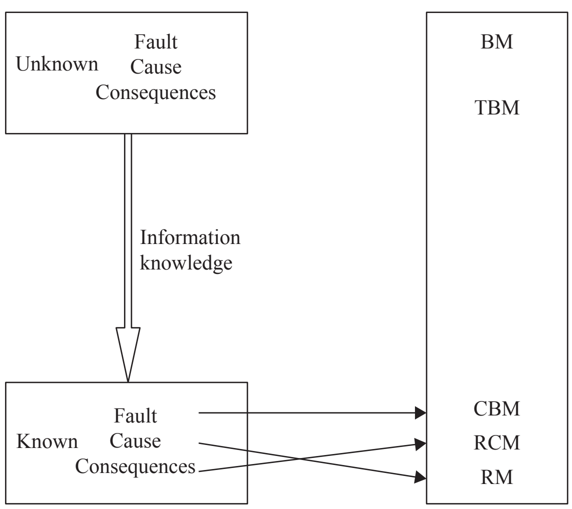

Fig. 1. Different methods of equipment knowledge maintenance.

expanding its space for development in recent years. The severe and complicated geographical situation in China provides a larger platform and an opportunity for the rapid development of the tunnel.

Relevant statistics show that 3784 railway tunnels were under construction in the country with a total length of 8692 km, and 4384 planned tunnels with a total length of 9345 km; 13 411 tunnels were operated with a total length of 13 038 km by the end of 2015. In 2015, 1316 new tunnels were opened to traffic, with a total length of 2160 km, of which 18 tunnels were over 10 km in length, with a total length of 245 km [8]. China has already built the largest tunnel in the world, and is the most productive and the fastest growing country in terms of construction technology. It is obvious that the market for tunnels is large in China. In addition, the tunnel requires repair and maintenance after a certain period of operation; however, most of the existing maintenance methods are based on troubleshooting individually followed by repair; this maintenance is less efficient and if the tunnel fails, it will be forced to stop running or risk more serious consequences. Hence, a new operational concept has drawn the attention of researchers, which is RCM.

3.1 Maintenance status of tunnel monitoring system

The maintenance of the operation tunnel monitoring system will focus on the monitoring of the overall operation status of all types of tunnels and tunnels, the necessary communication facilities for tunnel monitoring, the monitoring of the corresponding system equipment, and the emergency management of faults.

The tunnel monitoring system is critical in the operation of the entire tunnel, which is equivalent to a manager. Failure to effectively resolve or promptly repair the related facilities or systems can result in traffic confusion in urban areas. Therefore, the ultimate goal and the primary principle are to effectively prevent and handle the tunnel monitoring system.

In 2013, a heavy rainfall in Xiamen caused a flood in the Wucun Tunnel, which caused 3 h of traffic congestion. In 2017, because of heavy rains, the underground tunnels in the Beijing North Railway Station caused a flooding of nearly 1 km in the upper and lower reaches of the tunnel; the tunnel was 4.5 m high and the flooding water level was approximately 1.5 m away from the top of the tunnel. The incident also caused some sections of the Beijing urban area to be closed. Such tunnel accidents are common, and have brought serious economic losses and even personal injuries. The causes of these losses are not only natural disasters, but also the inability of the equipment to operate well and the lack of adequate precautions and emergency measures. Therefore, the optimum maintenance of all types of equipment in the tunnel is critical for the normal operation of the tunnel.

3.2 Problems in the maintenance of tunnel monitoring system

The common tunnel monitoring equipment has a strong ambiguity. Compared to other equipment, it has many special aspects such as the traditional tunnel monitoring system maintenance methods, the terminal products and equipment repair and maintenance, the scrapped equipment and product scheduling, as well as the improvement and maintenance after a certain number of years. This method is passive, and targeted maintenance does not exist. In a routine production, the maintenance personnel only repairs the “visible” damage of an equipment, rather than performing a regular and systematic testing and maintenance. In addition, an associated internal inspection and maintenance functions for “invisible” systems do not exist, and only a single regular maintenance based on conventional experience and the equipment service life that does not consider the actual operation of the equipment exists. However, the improved maintenance is also not specific, which does not consider the monitoring system conditions and the actual situation, and only relies on the traditional experience. The method cannot effectively avoid the loss, and cannot identify the hidden fault, which takes a long time to inspect and maintain. When unavoidable functional defects in the system and even serious failure consequences exist, such as system breakdowns, the maintenance personnel will not have the specific strategies and effective measures to handle them.

4 RCM analysis of tunnel

The tunnel monitoring system can ensure the traffic safety and avoid traffic accidents, and effectively reduce the pressure of the urban traffic. The analysis method of RCM can play a more important role if it is applied to the tunnel.

4.1 RCM analysis of tunnel monitoring system

The RCM analysis of the tunnel monitoring system should be performed from the following six aspects: ① fault information collection, ② analysis of fault mode, ③ clarification of failure cause, ④ assessment of the failure effects and consequences, ⑤ establishment of maintenance strategy, ⑥ continuous update of optimization policy repository according to the existing experience data.

Only a clear definition and understanding of the functions and failures of the various facilities in the tunnel can be described in detail for the six points above. Hence, we need to obtain the fault modes of all the devices, classify them according to the impact severity, and decide whether to begin preventive measures and execute them according to the sorting results. This is the failure mode and impact analysis (FMEA). The RCM analysis of the general process is shown in Fig. 2 [9,10].

4.2 Fault analysis of RCM in tunnel

In the RCM analysis of a tunnel, we must first identify the

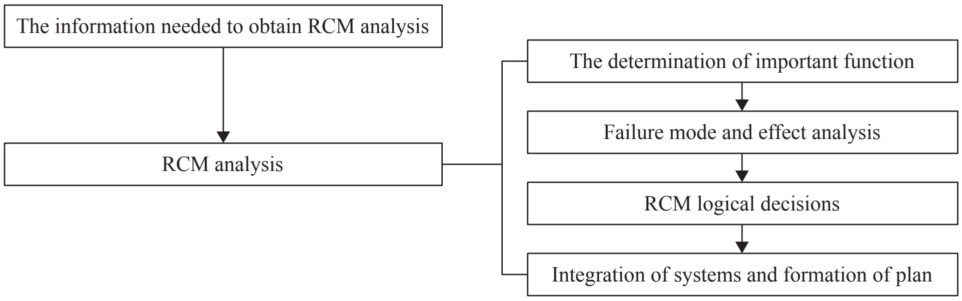

Fig. 2. RCM analysis process in general.

failure mode, and then analyze its reliability to achieve an effective maintenance management. The following is an example of the concrete tunnel fan analysis.

The mean time between failures (MTBF) means the average time of every two failure modes in a period of time.

MTBF= A period of total working time/failure number during this time (1)

according to the operation situation of the fan inside the tunnel that is operating within 3000 h, four faults had happened; according to formula (1), the average failure time is

$$\text{MTBF} = 3\,000 \div 4 = 750 \text{ h}$$

assuming that the failure rate of this fan is consistent with the index distribution,

$$f(t) = \lambda e^{-\lambda t} \tag{2}$$

its reliability is as follows:

$$R(t) = \int_t^{\infty} f(t)\mathrm{d}t = \int_t^{\infty} \lambda e^{-\lambda t}\mathrm{d}t = e^{-\lambda t} = e^{-t/\text{MTBF}} \tag{3}$$

in formula (3), $f(t)$ is the fan-failure distribution function; λ is the number of fan failure occurring in the agreed upon time period; t is the fan running time.

If the reliability requirements of this fan reached 80%, $R(t)$=0.8, then according to formula (3):

$$T = \ln R(t)\times\text{MTBF} = 0.233\times750 = 167 \text{ h}$$

The analysis above shows that if the reliability requirement of the fan reaches 80%, the maintenance cycle of the fan should be maintained at approximately 167 h. When the running time of the fan is stored in the tunnel monitoring platform, the system will automatically prompt the staff to perform the tunnel maintenance when the maintenance cycle is reached.

5 Application and benefit of applying RCM into tunnel

Although plenty of time and attention has been expended for the preparation, the feedback is far from the expectation, which is even much higher than the investment. Therefore, the application of RCM, which has the capacity of shrinking various costs, such as the cost on equipment repair and scrapping, repurchase, and people, desperately requires the improvement in tunnel repair strategy [11–13] as well as the increased level of organization and purpose during the process.

5.1 Reducing cost

The application of RCM can reduce the cost of repair, which can be shown in two aspects. First, the strategy arising from RCM is optimized. This means that not only the cost for daily repair will be reduced, the time interval of repair will also be extended. Second, to improve the system stability as well as reduce the failure rate and the repair cost of the large-scale experiment, this application includes some parts or some small parts' regular maintenance. Table 2 shows the comparison of the cost on repair during the period before and after the application of RCM.

5.2 Improving security

The security is composed of two perspectives to ensure the safety of traffic officers and the city environment. By applying RCM, a tunnel can cause the system to function stably, which can avoid the special failures attributed to the tunnel fault, or the damages on both the economy and human caused by nature [14]. The application of RCM is beneficial for the normal operation of a tunnel, by ensuring a smooth passage, and reducing the operation pressure and pollution from emissions. All these advantages contribute to the environment protection as well as reduce the negative effects on the citizens' health.

5.3 Increasing social efficiency

Traffic congestion can cause a significant damage to the national economy. It was reported in *People's Daily*, published in 2012, that the effects of traffic congestion will cause 15 cities in China to lose billions of yuan daily. We herein conclude that equipment repair is required when its stability has reached a certain level. This can be accomplished by the failure formation and reliable analysis of the tunnel equipment. Thus, the repairing work will reduce the probability of equipment failure and damage considerably. Therefore, the tunnel equipment will be in good working condition, thus reducing traffic congestions.

Table 2. Total cost comparison before and after repair.

Content	Traditional cost (ten thousand yuan)	RCM cost (ten thousand yuan)	Reduced cost (ten thousand yuan)	Reduced percentage (%)
Daily maintenance	672.43	552.2	120.23	17.88
Equipment maintenance	248.57	206.24	42.33	17.03
Cost	382	341	41	10.73
Others	117.22	118.43	−1.21	−1.03
Total	1420.22	1217.87	202.35	14.25

Meanwhile, when RCM for failure analysis is applied for the tunnel, various optimized strategies will be performed based on the distinct situations to ensure a normal operation that will contribute in both improving the citizens' safety and reducing the damage in the economy.

6 Conclusions

RCM is a type of modern repairing and managing strategy. Compared with other traditional methods, its advantages are proven in every area. Its peculiarity such as practice, science, profession, and high efficiency renders it a unique method, and is inexorable in the future repairing and managing strategy. This work combines the tunnel repairing and common problems occurring in China, applies the analysis principal into it creatively, and offers a type of efficient management strategy, whose purpose is to provide a better management, repairing, and motion with limited resources. It is considered that with the wide adoption of the functional tunnel domestically, the high efficiency and practice of RCM will be better developed.

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