Research on Assessment of Highway Tunnel Operating Safety

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Abstract. The operating safety of highway tunnels is governed by a complex system of people-vehicle-tunnel-environment and influenced by many factors. Its assessment is complex and unique to the specific tunnel. In this paper we discuss the assessment of the operating safety of highway tunnels from three aspects of rating, risk evaluation and resiliency, and propose the concept of operating safety resiliency of highway tunnels. We also summarize prior research in these aspects and analyze advantages and disadvantages of each assessment method.

1. Introduction

A tunnel is a semi-concealed structure with confined space. In the event of an emergency, the consequences are more severe than on open road outside the tunnel. On March 1, 2014 a serious hazardous goods explosion occurred in Yanhou Tunnel of Jincheng-Jiyuan Expressway in Shanxi, resulting in 40 deaths, 12 injuries, 42 vehicles being destroyed, direct economic loss of RMB81.97 million and severe social impact.

As of the end of 2017 a total of 16,229 highway tunnels covering 15285.1km had been in service in China, and highway tunnels are increasing by more than 10% a year [1]. As their service time increases, the operating safety of China’s highway tunnels faces grave challenges due to tunneling quality defects, material deterioration, facility ageing, complex traffic mix, outdated traffic standard, increasingly frequent actual and extreme disasters, strained resources for maintenance and inadequate experience in management and maintenance.

It is therefore necessary to study the operating safety of highway tunnels so as to reduce accident occurrences, mitigate adverse consequences of accidents and increase operating safety of the tunnels.

2. Research Direction of Assessment of Highway Tunnel Operating Safety

The operating safety of highway tunnels is governed by a complex system of people-vehicle-tunnel-environment and influenced by many interconnected and complementary factors. For a specific tunnel, its operating safety is also influenced by its unique features. Consequently, the assessment of the operating safety of highway tunnels is complex and on a case-by-case basis.

The assessment of the operating safety of highway tunnels is divided into the following three categories.
In research on influencing factors of highway tunnel operating safety since the start of the 1980s, the operating safety of highway tunnels is classified according to key indicators.

At the end of last century, risk theory was introduced to the operating safety of highway tunnels to assess risks for the operating safety of highway tunnels.

Recently the resiliency theory has been introduced to the operating safety of highway tunnels for relevant research. Such research is still in initial stage.

3. Existing Researches at Home and Abroad

3.1. Existing research on rating of the operating safety of highway tunnels

In the 1980s Japan issued safety rating standard for highway tunnels in which highway tunnels are classified into 5 levels by tunnel length and traffic volume based on past accidents and fire occurrence probability [2]. In the British publication Design Manual for Roads and Bridges (DMRB), a rating approach similar to Japan's has been adopted [3].

In 1999 Professor Alfred Hack from Germany, Dr. Matousek from Switzerland et al. performed safety assessment on 20 long and super long tunnels on major tourist routes in Europe, compared ten safety indicators including tunnel system, fire prevention methods and traffic control and proposed a series of criteria for safety rating assessment for highway tunnels.

Regarding operating safety rating evaluation for highway tunnels, a typical example is the tunnel safety rating method proposed in the European Tunnel Assessment Program (Euro Tap) [5, 6]. The flow of this evaluation method is presented in Fig. 1.

![Flowchart of the evaluation for tunnel safety](image)

**Fig 1. Flowchart of the evaluation for tunnel safety**

In China Xia Yongxu, Han Zhi, Pan Zhengzhong et al. [7-10] analyzed the influencing factors of the operating safety of highway tunnels, combined fuzzy mathematics, analytic hierarchy process and Delphi expert method to establish an indicator system for operating safety rating for highway tunnels and performed study on rating of highway tunnels.

3.2. Existing research on operating safety risk evaluation for highway tunnels

The operating safety of highway tunnels may be defined as a set of probabilities of potentially adverse events and possible consequences of casualties, economic loss, environmental damage or decreased traffic capacity during operation of a highway tunnel. The risk-based analytic method allows comprehensive consideration of characteristics specific to individual tunnels and structured and transparent evaluation of risks for a certain tunnel. See Fig. 2 for the flowchart.
Operating risk assessment for highway tunnels involves evaluating risks to the tunnel on the basis of its characteristic indicators (scene frequency, consequence and influencing parameters), including generic method, scene-based method and system-based method [11].

The scene-based method involves analysis of individual scene on the basis of its characteristic indicators and is mainly intended for detailed investigation of a specific problem of the tunnel such as optimization of escape route design.

The system-based method considers all relevant events or scenes that may affect personnel in the system under consideration. The risk is quantified by combining the probabilities and consequences of each scene. The overall risk to the tunnel is obtained by summing local risks to all scenes. See Fig. 3.

Fig 2. Flowchart of the procedure for risk assessment

Fig 3. Risk assessment – Example of system-based approach
Outside China, European countries did much research on assessment of highway tunnel operating risk. As required by the Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road, European countries must perform tunnel risk assessment. Some countries issued their own risk assessment methods in accordance with local conditions, including the UK, France and Austria. In China, no systematic in-depth research has been done on operating risk assessment for highway tunnels.

3.3. Existing research on resiliency in highway tunnel operating safety

Resiliency in highway tunnel operating safety can be defined as the ability of an in-service highway tunnel to maintain normal operation, quickly recover and optimize tunnel operating safety in certain time and place in the face of the impact and interference of adverse events.

The theory of highway tunnel resiliency focuses on dynamic behavior and symptoms of tunnel system throughout the effect of adverse events. The resiliency in highway tunnel operating safety can be explained in the following 4 aspects: the ability to reduce the probability of operational accidents; the ability to reduce losses from operational accidents; the ability to quickly get the traffic moving again; and the ability to improve operating safety level [12].

The resiliency in highway tunnel operating safety is closely related to the robustness, redundancy, timeliness and activeness of the tunnel system.

Robustness means the ability to maintain structural stability and avoid collapse or encroach on construction clearance after deficiencies have appeared in tunnel structure. It is influenced mainly by the health status of the tunnel structure.

Redundancy means the reliability of tunnel systems to provide design functions and the replaceability of safety facilities.

Timeliness means the length of time required to get the traffic moving again after adverse events. It is influenced by the operating agency's ability to control disaster and disaster relief level.

Activeness means the ability to mobilize emergency response resources in the event of an emergency. It is influenced by available resources near the tunnel.

Because the resiliency has just been introduced to the field of research on assessing highway tunnel operating safety, research on its assessment method and model is ongoing.

4. Comparative Analysis

(1) Rating of highway tunnel operating safety

Overall, current rating research on highway tunnel operating safety mostly involves selecting indicators to quantify key factors influencing highway tunnel operating safety and establishing assessment and rating criteria using corresponding specifications, standards and practical experience.

This method of assessing highway tunnel operating safety is straightforward, easy to perform and promote and facilitates assessment and mutual comparison. By quantifying qualitative indicators by fuzzy assessment method, the highway tunnel operating safety can be assessed comprehensively. This is of significant reference for solving the problem of highway tunnel safety assessment in China.

However, the operating safety status of highway tunnel is a concept with rich connotations and unclear extensions that is influenced by many complex factors. The established assessment indicator system is hard to improve. Meanwhile, the assessment does not take into account characteristics of individual tunnels and is influenced considerably by subjective factors.

In addition, the research on rating of highway tunnel operating safety cannot assess risks for specific types of accident and correlate assessment results to consequences such as casualties, economic loss, environmental damage and social impact.

(2) Risk evaluation for highway tunnel operating safety

With adverse events (scenes) as the core, the risk evaluation for highway tunnel operating safety can directly provide quantified values (anticipated values) of consequences such as casualties through deduction of adverse scenes, visually exhibit risk levels and fully display probability and loss information for various risks (FN curve).
The risk evaluation for highway tunnel operating safety is flexible and applicable to specific disaster scenes and different research depths. It can be used to study the effect of different safety measures in risk accidents and to compare risk evaluation results for different tunnels.

However, this risk-based method has some limitations from the highway tunnel safety point of view.

First, risk evaluation uses specific accident scenes as domain of discourse. It is difficult to accurately conceive initial adverse scene in a highly complex system, let alone list them exhaustively [14]. As a result, the presence of "residual risks" cannot be considered. Second, this method requires analysis with computer software, involving complex computation. The depth during modeling is uncertain and its accuracy and reliability remains to be verified. Last, it is sometimes difficult to obtain data; meanwhile, application of large sample data to specific system objects may lead to misleading estimate.

(3) Resiliency in highway tunnel operating safety

Resiliency in highway tunnel operating safety has evolved in some way in study philosophy and focuses on the entire process of adverse events. It studies highway tunnel operating safety from the time dimension within the service life of the highway tunnel.

However, main challenges of risk assessment still apply to resiliency research; meanwhile, many new problems remain to be solved because study on resiliency in highway tunnel operating safety is still in initial stage.

The resiliency in highway tunnel operating safety depends on deduction of tunnel system performance in specific scenes. Initial setting of the scene is different from actual conditions. The evolutionary processes of adverse events are also uncertain.

Meanwhile, due to consideration given to the full process of adverse events, the research on resiliency in highway tunnel operating safety needs to take account of the tunnel system's ability to perceive, forecast, respond and learn. This ability is influenced considerably by people and organization behaviors. Compared with physical system modeling, the modeling of people and organization behaviors is influenced by more complex factors. This results in a complex and uncertain resiliency assessment model.

5. Conclusions

It should be noted that the rating assessment for highway tunnel operating safety, risk evaluation for highway tunnel operating safety and research on resiliency in highway tunnel operating safety all simplify actual conditions to some degree. Each type of research has its own advantages and disadvantages. In the context of research on operating safety assessment for highway tunnels, various researches will be mutually reinforcing and complementary. Rating assessment and risk evaluation are analytical methods while resiliency improvement is the final goal.

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