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Technical Condition and Disease Analysis of Civil Structure of Highway Tunnels in Hebei Province

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Abstract: Based on the latest regular inspection data of civil engineering structures from 639 highway tunnels in Hebei Province, this article reveals the relationship between different road technical grades, tunnel types, and the technical conditions of civil engineering structures through multi-dimensional statistical analysis of technical conditions. It also analyzes and summarizes the frequently occurring sub-items of tunnel civil engineering structural defects, as well as common defect types and causes. This has important practical value for tunnel maintenance and management units to optimize maintenance strategies and improve management and maintenance levels.

Keywords: Highway tunnel; Civil engineering structure; Technical condition analysis; Disease analysis

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1. Introduction

As an important component of transportation infrastructure, the structural safety of highway tunnels is directly related to the traffic capacity and operational safety of road networks. With the continuous increase in the operational lifespan of highway tunnels in China, various defects have gradually emerged in tunnel civil structures under the combined effects of complex geological conditions, heavy traffic loads, and environmental erosion, posing severe challenges to maintenance and management work [1]. In recent years, domestic scholars have conducted certain research on tunnel technical conditions and disease mechanisms. For example, Liu Wenbin et al. analyzed regular inspections of 98 highway tunnels and found that lining damage, water leakage, pavement, and drainage facilities are the main issues in the civil structures of highway tunnels in southern provinces of China [2]. Luo Ziqing et al. analyzed the defects in the civil structures of 111 highway tunnels in karst areas in central and western Guangxi and found that these defects are mainly concentrated in the lining, portal, maintenance roads, and drainage facilities [3]. Zheng Kexi et al. established a knowledge base of civil structural defects in operational tunnels based on existing tunnel inspection data [4]. Chen Yuanyuan and Wang Jinyu et al. also summarized common defects and their causes

in tunnel civil structures during operation based on inspection data [5,6]. In summary, although domestic scholars have made some progress in research on technical conditions and disease mechanisms, systematic research on a large sample size at the provincial level is still relatively lacking. Especially for Hebei Province, as a transportation hub in North China, the analysis of the technical conditions of its tunnel civil structures holds significant reference value for similar regions.

2. Project overview

The operational environment of highway tunnels in Hebei Province is complex, and due to the long-term combined effects of diverse geological conditions, heavy traffic, and environmental factors, the problems of civil engineering structural defects are increasingly evident.

To systematically evaluate the technical conditions of civil engineering structures with different technical levels and tunnel types, and to reveal the distribution patterns and causes of typical defects, a total of 639 tunnels were included in this statistical analysis. According to the technical level of tunnels, there are 499 national expressway tunnels, accounting for 78.09%, and 140 national and provincial trunk line tunnels, accounting for 21.91%, as shown in **Figure 1**. According to the tunnel type, there are 242 short tunnels ($L \leq 500$ m), accounting for 37.87%, 140 medium tunnels (500 m $< L \leq$ 1000 m), accounting for 21.91%, 197 long tunnels (1000 m $< L \leq$ 3000 m), accounting for 30.83%, and 60 extra-long tunnels ($L >$ 3000 m), accounting for 9.39% [7]. Refer **Figure 2**.

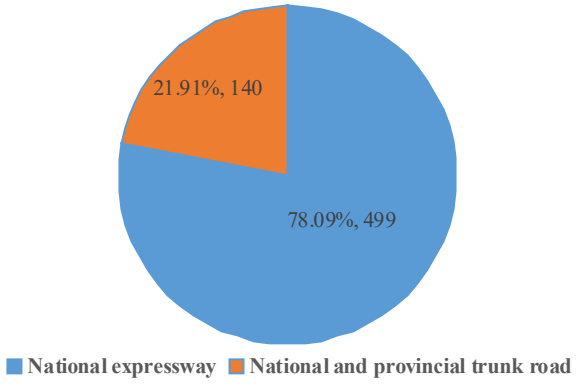

Figure 1. Statistical chart of tunnel technology classification.

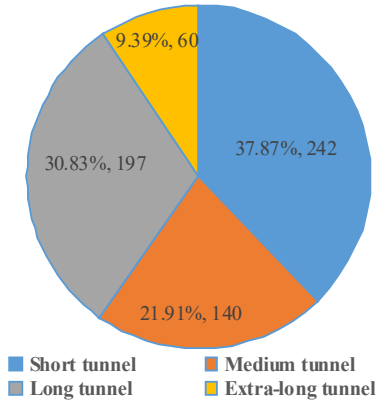

Figure 2. Statistical chart of tunnel type classification.

3. Analysis of technical conditions of civil engineering structures

3.1. Relationship between technical conditions and road technical grades

To explore the differences in the technical condition of tunnel civil structures under different road technical grades, and thereby provide a basis for maintenance units to reasonably formulate targeted maintenance management strategies, this paper takes 639 tunnels in Hebei Province as the research objects and conducts a comparative analysis of the technical conditions of their civil structures according to the road technical grade they belong to. The relevant results are shown in **Figure 3** and **4**. The results show that the overall technical condition of tunnel civil structures in Hebei Province is at a good level, but there are significant differences among tunnels on different grades of roads: the average score of the civil structure technical condition for 499 national expressway tunnels is 81.55, with 99.80% of tunnels rated as type 1 and type 2, indicating that the overall structural condition of national expressway tunnels is good and the maintenance management level is high. In contrast, the average score of the civil structure technical condition for 140 national and provincial trunk line tunnels is 79.62, with 88.57% of tunnels rated as type 1 and type 2. Although generally still good, it is obviously inferior to that of national expressway tunnels. In addition, among the national and provincial trunk line tunnels, there are still 16 tunnels with civil structure technical conditions rated as type 3 or above, accounting for 11.43%, meaning that these tunnels have relatively obvious structural defects and should be repaired and treated in a timely manner. Overall, the civil structure technical condition of national expressway tunnels is significantly better than that of national and provincial trunk line tunnels. Accordingly, Hebei Province should consolidate the existing high-standard maintenance management achievements of national expressway tunnels and proactively and effectively take improvement measures for the relatively weaker technical conditions of national and provincial trunk line tunnels.

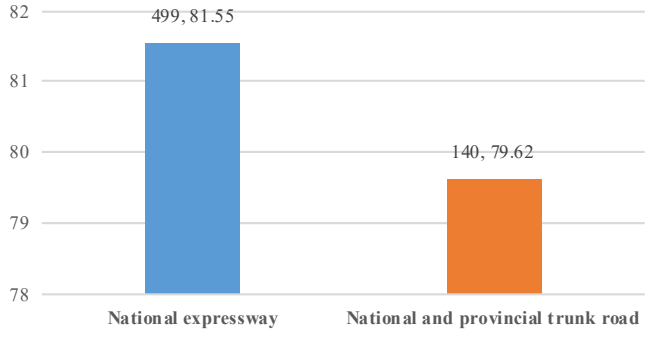

Figure 3. Average scores of tunnel technical conditions across different road technical grades.

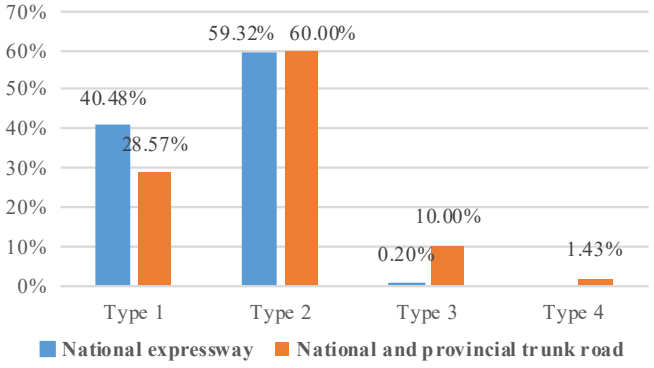

Figure 4. Percentage of tunnel technical conditions at different road technical grades.

3.2. Relationship between technical conditions and tunnel types

To explore the relationship between the technical condition of tunnel civil structures and tunnel types, and to provide a reliable basis for differentiated maintenance decisions, this paper takes 639 tunnels in Hebei Province as the research objects. The technical conditions of civil structures are compared and analyzed according to tunnel length categories, as shown in **Figures 5** to **7**. The results indicate that there is a certain correlation between the technical condition of tunnel civil structures and tunnel length: short tunnels have the best technical condition of civil structures, with an average technical condition score of 82.88, and tunnels rated as type 1 and type 2 account for 98.76% of the total sample. As tunnel length increases, the technical condition of civil structures shows a declining trend. The average scores for medium and long tunnels are 81.03 and 79.44, respectively, and the proportion of tunnels rated type 3 or above correspondingly rises. For medium tunnels, the proportion of Class 3 or above tunnels is 4.29%, and for long tunnels, it is 3.56%. However, the average technical condition score of extra-long tunnels slightly rebounds to 79.85, and the proportion of Class 1 and 2 tunnels rises to 98.34%, which is likely due to the resource preference and stricter management measures allocated to extra-long tunnels during operation and management.

Overall, it shows that the technical condition of tunnel civil structures becomes increasingly severe with the increase in tunnel length, and the difficulty and complexity of maintenance also correspondingly increase. However, examples of ultra-long tunnels also illustrate that appropriate resource investment and optimized management methods can mitigate or even reverse this negative trend. Therefore, in tunnel maintenance management, managing units should, while ensuring the safe operation of ultra-long tunnels, focus on medium- and long tunnels as key objects for improving technical condition and preventive maintenance.

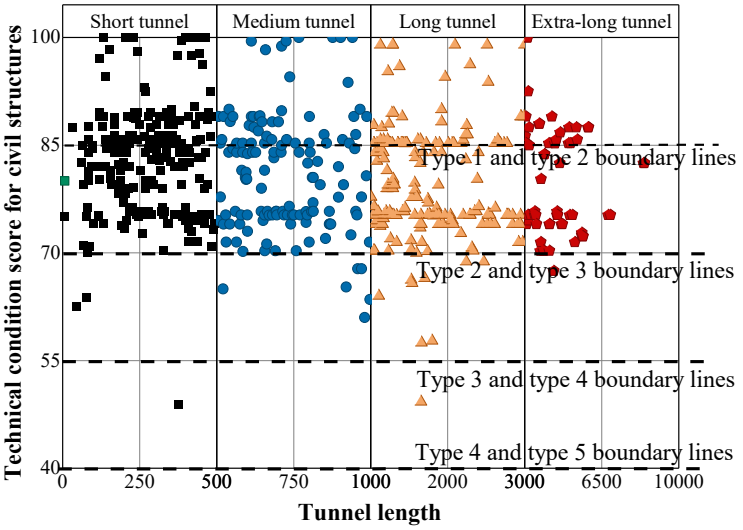

Figure 5. Relationship between technical condition score and tunnel type.

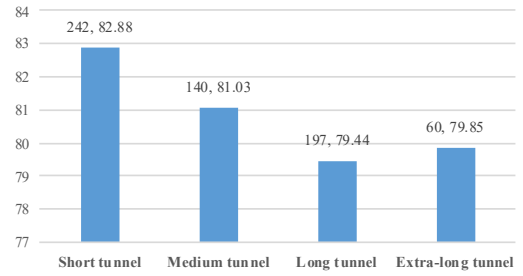

Figure 6. Average scores of different types of tunnel technology conditions.

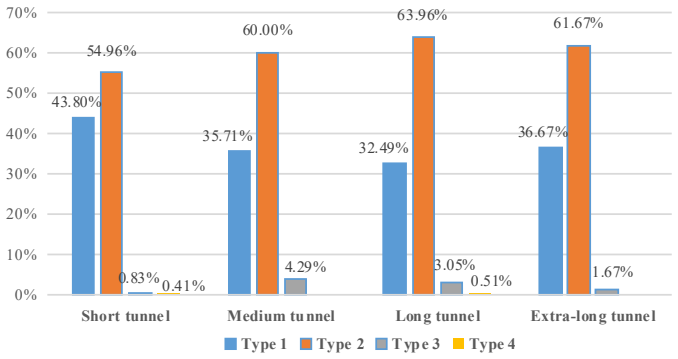

Figure 7. Percentage of different types of tunnel condition values.

4. Analysis of typical defects in civil engineering structures

To explore the main sub-item defects affecting the technical condition of tunnel civil engineering structures and provide a reference for maintenance and management by the maintenance and management unit, this paper statistically analyzes the proportion of each sub-item condition value in the latest regular inspection of 639 tunnel civil engineering structures, as shown in **Figure 8**. The results indicate that the defect rates of lining, pavement, maintenance access, and interior decoration in tunnel civil engineering structures are 91.24%, 73.08%, 72.14%, and 76.06%, respectively, which are the main sub-items with concentrated defects. The proportion of lining condition value 2 is as high as 41.31%, significantly higher than other sub-items, indicating that lining defects are often the most frequent and most influential defects on civil engineering structures, significantly restricting the technical condition rating of civil engineering structures. Although pavement, maintenance access, and interior decoration are mainly condition value 1 (67.14%, 71.36%, and 74.96%), the high proportion reflects widespread defects, requiring attention to long-term accumulated defects. The proportions of condition value 1 for portal, tunnel entrance, and sign markings are 12.99%, 25.35%, and 18.78%, respectively, indicating a certain range of minor defects. In comparison, the possibility of defects in drainage facilities and ceiling embedded parts is relatively low (both < 9%).

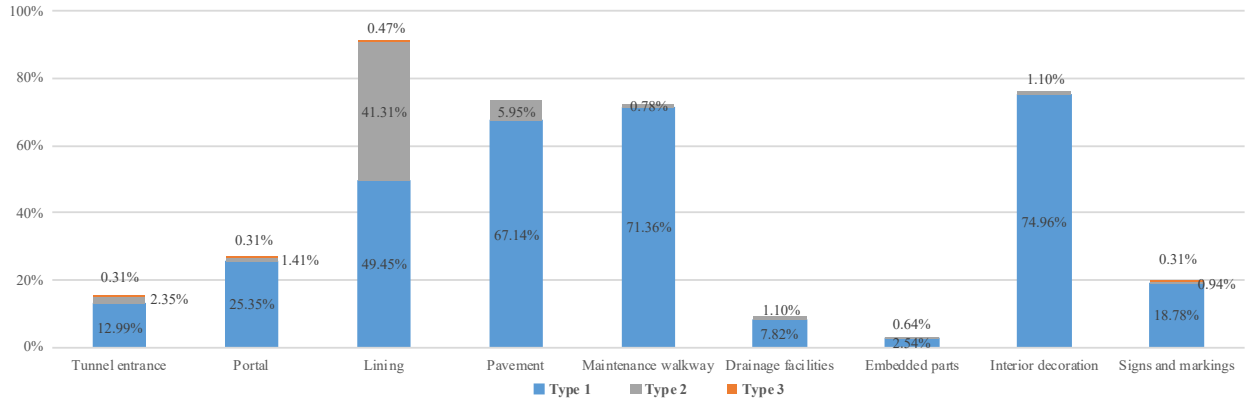

Figure 8. Percentage chart of sub-item status values for tunnel civil engineering structures.

Upon further analysis of the types and causes of defects, it was found that the lining often experiences leakage due to local failure of the waterproofing system, as well as cracks and damages caused by tunnel surrounding rock load, concrete deterioration, structural thermal expansion and contraction, and vehicle scratching; the pavement often suffers from cracks and potholes due to the load of heavy vehicles, broken tunnel base, or construction quality issues; the maintenance walkways often experience panel chipping, damage, and cracking due to insufficient strength of the cover plate, improper lifting and covering during maintenance construction, as well as side wall damage caused by vehicle collisions and scrapes; the interior decoration and sign markings often suffer from damage and dirt due to long operating hours and heavy traffic. Among these, lining and pavement may develop from small defects into large ones. It is recommended to prioritize the inspection and repair of lining and pavement during daily maintenance. At the same time, for high-frequency minor defects such as those on maintenance walkways and interior decoration, daily maintenance plans or preventive maintenance plans should be formulated to ensure the operational and structural safety of the tunnel.

5. Conclusion

Through statistical analysis of the most recent regular inspections of the civil structures of 639 highway tunnels in Hebei Province, this study reveals the relationship between the technical condition of tunnel civil structures and the tunnel road technical grade and tunnel type, and identifies the sub-items of tunnel civil structures that are prone to diseases, as well as common types of defects and their risk causes. The conclusions help tunnel management units optimize maintenance strategies, improve tunnel safety and service life, and reduce operational risks. Through this review, the main conclusions and recommendations of this thesis are as follows:

(1) The technical condition of the civil structure of national expressway tunnels is significantly better than that of national and provincial trunk line tunnels. Tunnel maintenance units should, while continuously consolidating the high-standard maintenance management achievements of national expressway tunnels, proactively and effectively take measures to improve the relatively weak technical aspects of national and provincial trunk line tunnels.

(2) As the tunnel length increases, the overall technical condition of the tunnel's civil structures tends to

decline, but it can be partially improved through resource allocation or management optimization. Maintenance units need to focus on enhancing the upkeep of medium- and long-length tunnels.

(3) Lining, pavement, maintenance access, and interior decoration are the main sub-items where civil engineering structural defects are concentrated in highway tunnels in Hebei Province. In particular, lining damage and water leakage are the most frequent and most influential defects in civil engineering structures. The maintenance unit needs to pay attention to inspection and repair, and strive to ensure the operation and structural safety of the tunnel.

Disclosure statement

The authors declare no conflict of interest.

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