Assessment system for shield tunnel serviceability

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Abstract: With the increase in tunnel construction scale and service time, the serviceability assessment of shield tunnels has become increasingly critical. The single assessment indicator is not detailed. However, the comprehensive assessment indicator is more qualitative and lacks a scientific basis. In response to this problem, an intact and efficient assessment system for shield tunnel serviceability is proposed. This assessment system combines rapid and detailed assessment. The rapid assessment uses the shield tunnel serviceability index to determine the safety level of tunnels. The tunnel needs to be assessed in detail to evaluate the structure’s safety, which is at the average level. The detailed assessment includes three parts. The convergent deformation of the tunnel is calculated based on the transverse mechanical model, the joint force is analyzed based on the longitudinal joint mechanical model, and the differential settlement is analyzed based on the theory of beam on elastic foundation. The mechanical state provides a basis for structural serviceability evaluation, disease causes, and disease management. The assessment system is applied to a specific tunnel section of the Guangzhou Metro. It can analyze the tunnel’s safety performance and guide maintenance scientifically and efficiently.

1. Introduction
At present, an increasing number of shield tunnels have been put into operation in China. The geotechnical conditions of shield tunnels are complex, the surrounding environment is sensitive, and the conditions are harsh. Once damaged, the shield tunnel is difficult or impossible to replace, inducing underground engineering disasters. As a result, experts have set high requirements on the serviceability assessment of shield tunnels.

Health evaluation methods of shield tunnels are mainly divided into single assessment indicators, mathematical models, and mechanical models. Single assessment indicators are the simplest and most widely used method in shield tunnel health assessment. They can classify different tunnel diseases [1,2]. Although single assessment indicators are practical and straightforward, they cannot reflect the comprehensive health status of the tunnel structure. Thus, they ultimately depend on the experience and judgment of experts. In terms of mathematical models, some researchers investigated the factors...
affecting the safety of shield tunnels and analyzed each element using the analytic hierarchy process and fuzzy comprehensive evaluation method [3,4,5]. Mathematical models can conveniently solve practical problems but do not consider the internal correlation between tunnel structural diseases. Regarding the mechanical models, some researchers classified the tunnel state according to the structural limit state and proposed a longitudinal joint opening calculation model to calculate the tunnel state [6,7]. However, mechanical models are highly complicated and time consuming, making them challenging to implement in engineering practice.

2. Assessment System

Basing from the research and analysis of health assessment methods, this paper introduces an assessment system combination of rapid and detailed assessment to evaluate the serviceability of shield tunnels. The rapid assessment classifies the structural safety performance of the tunnel according to the shield tunnel serviceability index. The detailed assessment analyzes the structural state of the shield tunnel on the basis of the transverse mechanical model, the longitudinal joint mechanical model, and the longitudinal mechanical model.

2.1 Rapid Assessment

When evaluating the serviceability of a shield tunnel, rapid assessment is initially carried out to screen the structure in an unfavorable state. The rapid assessment is based on the daily monitoring data of the shield tunnel to classify the safety level. With regard the shield tunnel structure, internal and external environment, daily monitoring, and other factors, the specific evaluation indicators are settlement, convergence, seepage, crack, spalling, staggered platforms, and joint opening.

2.1.1 Longitudinal deformation

According to on-site monitoring, part of the final settlement of shield tunnels is due to the overall settlement of the earth, and the overall settlement is not harmful to the tunnel itself. Therefore, the mean relative settlement and the mean differential settlement are selected as assessment indicators. The calculation formula is as follows:

\[
S_{\text{ave}} = \frac{\sum_{i=1}^{m} S_{r,i}}{m},
\]

\[
S_{\text{diff},i} = \frac{|S_{r,i} - S_{r,i-1}|}{l_{i,i-1}},
\]

\[
S_{\text{diff,ave}} = \frac{\sum_{i=2}^{m} S_{\text{diff},i}}{m-1},
\]

where \(S_{\text{ave}}\) is the mean differential settlement, \(m\) is the number of monitoring points, \(S_{r,i}\) is the i-th relative settlement monitoring value, \(S_{\text{diff},i}\) is the i-th differential settlement calculation value, \(l_{i,i-1}\) is the distance between the i-th and the (i-1)-th monitoring value, and \(S_{\text{diff,ave}}\) is the mean differential
settlement.

2.1.2 Transverse deformation

The average value of shield tunnel lining convergence is selected as the evaluation index of transverse deformation, and the calculation formula is as follows:

\[
C_{\text{ave}} = \frac{\sum_{i=1}^{m} |D_i - D|}{Dm} = \frac{\sum_{i=1}^{m} |\Delta_i|}{Dm},
\]

where \( C_{\text{ave}} \) is the mean convergence ratio, \( m \) is the number of monitoring points, \( D_i \) is the measured value of the outer diameter of the \( i \)-tunnel, \( D \) is the design value of outer tunnel diameter, and \( \Delta_i \) is the \( i \)-th measurement of lateral deformation.

2.1.3 Disease indicator

In the daily monitoring of shield tunnels, the allowable deformation of staggered platforms and cracks is small, and manual inspection is challenging to identify. Thus, the seepage \( d_1 \), crack \( d_c \), and spalling \( d_s \) are selected as disease indicators.

In the rapid assessment, six evaluation indicators are selected: \( S_{\text{ave}}, S_{\text{diff,ave}}, C_{\text{ave}}, d_1, d_c, \) and \( d_s \). Considering the experts’ evaluation of the relevant samples, we fit the quantitative relationship between the tunnel health status and the evaluation index and obtain the generalized formula of the shield tunnel serviceability index. In this way, the health status of the shield tunnel is divided into several safety levels.

\[
T_{\text{st}} = 0.77 + 0.16 \sqrt{S_{\text{ave}}} + 0.01S_{\text{diff,ave}} + 0.09C_{\text{ave}} + 0.08d_1 + 0.05d_c + 0.50d_s
\]

Given the similarity of relevant parameters, such as the diameter and buried depth of the subway shield tunnels in China, this formula is suitable for subway shield tunnels in a broad sense. Moreover, most of the subway tunnels in China have been operating for less than 20 years, and this formula is applicable. For tunnel structures more than 20 years in the future, sample data can be re-collected and fit, or the weight of the formula can be modified by considering the impact of index degradation [8].

| Safety level | Status  | Disease | Influence on tunnel safety   |
|--------------|---------|---------|-----------------------------|
| 1            | very good | very slight | no influence               |
| 2            | good     | slight   | no influence right now      |
| 3            | average  | common   | some influence in the future |
| 4            | bad      | serious  | some influence right now    |
| 5            | very bad | very serious | serious influence          |

2.2 Detailed Assessment

For shield tunnels with an average level obtained by the rapid assessment, a detailed assessment is required. The detailed assessment of structural safety is based on the transverse mechanical model, the
longitudinal mechanical model, and the joint mechanical model. It analyzes the mechanics of structure based on the three leading indicators of convergent tunnel deformation, longitudinal joint opening, and uneven settlement. It provides a basis for structural performance evaluation, disease causes, and disease management.

2.2.1 Transverse mechanical model
The load–structure model is used to determine the load in the convergent deformation because its calculation method is simple and the workload is small. It has a clear concept of force and a straightforward safety factor evaluation. The load pattern is shown in Figure 1. The detailed calculation process of each parameter can be according to the specification.

![Figure 1. Calculation diagram](image)

The beam-spring model is used to simulate the tunnel ring structure, in which the segments use beam elements and the joints use spring elements. The finite element analysis software is used to analyze the convergent tunnel deformation. In the 2D model, the spring element only considers its rotational stiffness without considering the effects of axial and shear stiffness. Rotational stiffness can be equivalently represented by a double-line model simulated by the combin39 element in Ansys. The rotational stiffness under positive and negative bending moments can adopt different double-line models [9], as shown in Figure 2.

![Figure 2. Double-line model](image)

The convergent deformation in the operating tunnel is mainly related to the lateral pressure coefficient of the soil, the ground load, the resistance coefficient of the foundation, and the rotation
stiffness of the joint. The internal force corresponding to the convergent tunnel deformation can be obtained through finite element analysis and used to analyze the force of the tunnel and the cause of the convergent deformation.

2.2.2 Joint mechanical model

Longitudinal joints are the weak parts of the segment ring, and the load-bearing capacity of the segment ring is mostly controlled by the load-bearing capacity of the joint [10]. Mechanical equilibrium equations are established using the force characteristics of longitudinal joints under the action of positive and negative bending moments. These equations simply explain the force mode when the positive bending moment on the joint is small.

![Figure 3. Sectional deformation and mechanical balance diagram](image)

When the positive bending moment of the joint is small, the cross-section bolts, the elastic gasket, and the concrete in the compression zone participate in the force. The mechanical equilibrium equation of the joint surface is

\[
\sum X = 0, \quad N + nT_b - F_c - F_s = 0 \quad \text{(6)}
\]

\[
\sum M = 0, \quad Ne - F_c \left(\frac{h}{2} - h_s - h_f - \frac{1}{2} \beta y\right) - nT_b (h_b - h_s) - \frac{1}{2} F_s (h - 2h_f - h_s) = 0 \quad \text{(7)}
\]

where \(N\) is the axial force of joint section, \(T_b\) is the bolt tensile force, \(F_c\) is the resulting force of concrete compressive stress, \(F_s\) is the resulting force of gasket compressive stress, \(y\) is the height of concrete compression zone, \(h\) is the segment thickness, \(h_b\) is the distance from bolt to external of segment, \(h_s\) is the the height of gasket, \(h_f\) is the the height of concrete compressive zone external edge, \(n\) is the number of bolts, and \(\beta\) is the equivalent rectangular coefficient.

For an interval tunnel, we select the section to be evaluated and check the segment and geology of the section. Finally, we determine the buried depth of the interface, the bolt pre-tightening force, the damage depth, the lateral pressure coefficient, and the foundation coefficient to study the opening of the longitudinal joint. The development trend of the longitudinal joint opening can be obtained. The corresponding relationship between the opening amount and the bending moment value is obtained so that the force of the joint under the actual opening state can be judged.
2.2.3 Longitudinal mechanical model

Analysis of tunnel longitudinal deformation based on the theory of beam on elastic foundation indicates that the longitudinal length of the subway shield tunnel is much larger than the diameter of the tunnel segment ring. Thus, the tunnel can be regarded as a longitudinal beam. The tunnel is a homogeneous ring in the transverse direction. In the longitudinal direction, the shield tunnel composed of joints and segments is equivalent to a uniform and infinite beam with the same stiffness and structural characteristics. It can be solved using the differential equation of the elastic curve of the beam under an external load [11].

$$EI\left(\frac{d^4y}{dx^4} + 4\beta^4y\right) = q(x), \quad (8)$$

where $EI$ is the equivalent stiffness, $\beta$ is the foundation flexibility coefficient, $y$ is the tunnel settlement, $k$ is the coefficient of subgrade reaction, and $D$ is the tunnel outer diameter.

The longitudinal deformation performance of the shield tunnel is much weaker than the transverse force performance of the structure [12]. When the longitudinal deformation or deformation curvature reaches a specific value, circumferential joints may excessively open. According to the actual settlement data, the tunnel’s longitudinal deformation curvature and settlement curve can be obtained. The theoretical formula can be used to obtain the internal force of the tunnel and bolts and analyze the possible causes of settlement deformation.

3. Engineering Applications

A specific tunnel section of the Guangzhou Metro is selected as the engineering case, and the section is a two-way tunnel (divided into left and right lines). The section is assembled with staggered joints. The outer diameter of the lining is 6.0 m, the inner diameter is 5.4 m, the thickness is 0.3 m, and the ring width is 1.5 m. A particular section is in the residual granite soil. The differential settlement is relatively large. Thus, the health status of the section needs to be evaluated.

With the assessment system, the tunnel section is initially evaluated by rapid assessment. We transform the monitoring values of the tunnel into evaluation indexes and substitute them into the formula of the service performance index. Furthermore, the $T_{SI}$ calculation result is 3.0, which corresponds to the average security level. Therefore, the tunnel section needs to be evaluated in detailed assessment.

Detailed assessment includes three parts. In the transverse mechanical model evaluation, some tunnel sections are selected and analyzed by Ansys to understand the convergent tunnel deformation. Finally, the maximum convergent deformation of the tunnel diameter is 5.8%. The convergent tunnel deformation in actual monitoring is small, which meets the safety requirements.
This paper selects the tunnel ring to calculate and obtain the relationship between joint opening and bending moment in the longitudinal joint mechanical model. The joint force includes four stages: joint full-section compression, transition, edge concrete contact, and bolt yield. The comparison of the actual longitudinal joint opening shows that the tunnel joint is in a transitional stage.

In the longitudinal mechanical model evaluation, the tunnel force is inferred through the settlement curve of the tunnel. The iterative calculation program is calculated to obtain the actual bending moment and shear force of the tunnel. Compared with the results of finite element analysis, the difference is not significant. The tunnel section is determined at an average safety level through the assessment system of shield tunnels and does not require maintenance.

4. Conclusions
This study evaluates the serviceability assessment system of shield tunnels and obtains the overall operation of tunnel health evaluation. This system includes two parts: rapid and detailed assessment. The results obtained are as follows:

(1) The rapid assessment is based on the shield tunnel serviceability index to classify the structure. The tunnel structure at the average safety level needs to be evaluated in detail.

(2) The detailed assessment is based on the structural transverse mechanics model, the longitudinal mechanics model, and the joint mechanical model. It analyzes the mechanical state of the structure based on the three leading indicators of the tunnel: longitudinal joint opening, convergent...
deformation, and uneven settlement.

(3) The application of the serviceability assessment system to a particular tunnel section of the Guangzhou Metro is demonstrated.

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5. References

[1] Luo X and Xia C C 2006 Current situation and problems of classification of tunnel diseases Chinese Journal of Underground Space and Engineering 5 877–80
[2] Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2019 Code for design of metro GB50117-2019 (China Architecture & Building Press)
[3] Lin N 2009 Study on structure safety evaluation index system and standard of the subway (Shanghai: Tongji University)
[4] Ye Y 2007 Research on deformation and method of health diagnose of operational subway structures in soft soil (Shanghai: Tongji University)
[5] Su H 2018 Research on structural safety assessment for shield tunnel in shanghai Chinese Journal of Underground Space and Engineering 14(S2) 940–6
[6] Yuan Y, Bai Y and Liu J 2012 Assessment service state of tunnel structure Tunnelling and Underground Space Technology 27 72–85
[7] Li X, Yan Z and Wang Z 2015 A progressive model to simulate the full mechanical behavior of concrete segmental lining longitudinal joints Tunnelling and Underground Space Technology 93 97–113
[8] Zhu W, Zhong X C and Qin J S 2006 Mechanical analysis of segment joint of shield tunnel and research on bilinear joint stiffness model Rock and Soil Mechanics 12 2154–05
[9] Zhuo L H, Yuan Q, Li X J and Lin X D 2019 Application of Tunnel serviceability index in Guangzhou Metro health assessment Urban Mass Transit 22 140–4.
[10] Liu J H and Hou X Y 1991 Shield tunnel (Beijing: China Railway Publishing house)
[11] Long Y Q 1991 Calculation of elastic foundation beam (Beijing: People's Education Press)
[12] Lin Y G, Liao S M and Liu G B 2000 Discussion on influencing factors of longitudinal deformation of metro tunnel Chinese Journal of Underground Space and Engineering 20 264–7