Recent Trends in Design Technology of Cut and Cover Tunnels for Railways

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Cut and cover tunnels for railways in Japan are designed according to the Design Standards for Railway Structures and Commentary (Cut and Cover Tunnels). The standard was published about 15 years ago. Subsequently, the design of railway structures, except tunnels, shifted to a performance-based design system. Therefore, a committee was established to revise the Design Standards for Railway Structures and Commentary (Cut and Cover Tunnels) in 2014. The committee completed a draft new set of standards in 2017. This paper discusses recent trends in the design technology of cut and cover tunnels for railways, with a focus on the contents of the committee's revised draft.

Keywords: cut and cover tunnels, design standards, performance-based design, performance verification-based design

1. Introduction

Cut and cover railway tunnels are designed according to the "Design Standards for Railway Structures and Commentary (Cut and Cover Tunnels)" [1], and specifically to the limit-state design method [2]. More than 15 years have passed since the standard was published in March 2001. Meanwhile, the “Ministerial Ordinance to Provide Technical Regulatory Standards on Railways (Ministry of Land, Infrastructure, Transport and Tourism Ordinance No. 151)” [3] adopted the principle of performance-based design. This ministerial ordinance led to a change in design standards for railway structures to performance verification-based design, except for tunnels, and design standards and related guidelines and design calculation models were created. In addition, in FY 2012 the Japan Society of Civil Engineers started introducing performance based-design concepts into the Standard Specifications for Tunneling (Cut-and-Cover Tunnels), completing the revision in FY 2016 [4].

Within the scope of the Design Standards for Railway Structures, only tunnels do not yet have performance verification-based design standards, namely, Cut and Cover Tunnels, Shield Tunnels and Mountain Tunnels. There have been pressing needs for, among other things, the adoption of performance specific concepts, consideration for maintainability and the introduction of the latest technologies.

With the above circumstances in mind, in January 2014 a committee to work on the Design Standards for Railway Structures (Cut and Cover Tunnel) was set up and chaired by Visiting Professor Y. Koyama of Ritsumeikan University, with Professor H. Akagi of Waseda University as secretary general under the guidance of the Ministry of Land, Infrastructure, Transport and Tourism with the aim of revising the Cut and Cover Tunnel Standards ahead of the two other of the three tunneling methods, i.e. the shield tunneling and mountain tunneling methods, as the cut and cover method was thought to be easier to type of tunnel to introduce performance verification-based design first. Having spent three years studying the subject, in January 2017 the committee finalized a draft revision of the Cut and Cover Tunnel Standards. In this Perspective, general trends in performance verification-based design technologies for cut and cover railway tunnels will be discussed centering on the discussions in the committee on the Design Standards for Railway Structures and Commentary (Cut and Cover Tunnel).

2. Design technologies for cut and cover railway tunnels

The committee on the Design Standards for Railway Structures (Cut and Cover Tunnels) discussed the revision based on the following key concepts to underpin the Cut and Cover Tunnel Standards: (1) switch to performance verification-based design, (2) improvement in maintainability, (3) application to large underground stations and (4) performance verification for when underground diaphragm walls are used as part of the main tunnel structure.

2.1 Switch to performance verification-based design

Performance verification-based design not only helps cut construction costs and improve the degree of design freedom but enables direct numerical and empirical study of harmful alterations to existing tunnels using performance parameters (e.g. water leakage for water-tightness, degradation of materials for durability and convergence for saving space). Based on this, switching to performance verification-based design is thought to contribute to the design of safer and more durable structures and therefore performance parameters that are unique to cut and cover tunnels and that factor in maintainability were identified. Table 1 shows the performance parameters of cut and cover tunnels for each structural performance requirement and
whether verification is required for each parameter.

In addition, besides the performance requirements that must be satisfied by both cut and cover tunnels that do not support trains on the ground and those that do, extra performance requirements for the latter type of cut and cover tunnels were identified. For tunnels with a shallow earth covering, the following performance parameters must be verified:

- Vehicle running safety on the ground;
- Risk of fatigue fracture for upper decks;
- Usability with respect to the ride comfort of vehicles on the ground.

These considerations were also adopted for application to box culvert-type crossing structures under railways.
2.2 Improvement in maintainability

Many of the harmful alterations seen on cut and cover tunnels involve the degradation of materials used, with water leakage like the one in Fig. 1 being the primary cause. Where leaking water contains salt like in in tidal reaches or harmful substances, repeated repairs are often required as degradation recurs. To extend the serviceable life of a tunnel, it is considered extremely important to adopt measures to prevent material degradation and cracking as well as designing new tunnels with reduced amounts of leaking water. Given the above, a maintenance database was analyzed focusing on durability and water-tightness and the results were reflected in design methods especially with respect to durability and structural details.

Amongst other things, the following findings were obtained about chloride ions:

- In and around the areas with water leakage, the concentration of chloride ions on the surface and inside concrete increases and can rise far beyond the concentration limit (1.2 kg/m$^3$).
- In such cases, the concentration of chloride ions is even greater near water leakages that are subject to repeated dry-to-wet-to-dry cycles.

According to the evaluation criteria for the concentrations of water components in Germany (DIN: Deutsche Industrie Normen) and tap water quality standards, the corrosive impact of chloride ions in the groundwater on steel members at tunnel construction sites can normally be considered minimal if the concentration of chloride ions in the groundwater at the sites is 200 mg/L (0.2 kg/m$^3$), the standard value of the above, or less. Therefore, it was concluded that related examination was not necessary if the standard value was not exceeded. Harmful alteration surveys of existing structures, seepage flow analysis and other studies found that the areas where the concentration of chloride ions in the groundwater was 200 mg/L (0.2 kg/m$^3$) or above can include filled-in ground and areas within 100 m from tidal rivers, which are shown in Fig. 2 [8].

2.3 Application to large underground stations

When designing cut and cover tunnels, the ground is normally modeled as a set of springs and the ground deformation coefficient is calculated using equations that factor in dependence on loading width. For example, the vertical ground deformation coefficient for the bottom surface of a lower deck can be calculated using (1) and (2) and the ground deformation coefficient diminishes as conversion width (the size of the cut and cover tunnel) increases.

\[
k_v = 5.1 \rho_{gk} E_v B_v^{-3/4}
\]  
(1)

where $k_v$: Vertical ground deformation coefficient (kN/m$^3$), $\rho_{gk}$: Ground correction coefficient for ground deformation coefficient, $E_v$: Design modulus of ground deformation (kN/m$^3$), $B_v$: Conversion width (m). 

\[
B_v = (B \cdot L)^{1/2}
\]  
(2)

where $B$: Reference conversion width (m), $L$: Longitudinal length of tunnel (m)\(^6\)

\(^6\) L can be either a joint interval calculated using (2) or the lower deck width, whichever is smaller.

In recent years, the cut-and-cover tunneling method has been increasingly used to construct large-scale underground stations. The equation to calculate ground deformation coefficient indicates that the coefficient becomes smaller as the size of the construction increases. In reality, ground deformation coefficient shows dependence on displacement level, i.e. the coefficient changes as the displacement level changes. Cut and cover tunnels generally are lighter than the excavated earth and therefore have low displacement levels. Increasing the size of cut and cover tunnels makes no significant changes in displacement levels. For those reasons, ground deformation coefficient can be underestimated when it is calculated using the equation above.

Given the above, the following steps were taken: Considering that cut and cover tunnels between stations are generally about 10 m wide, a conversion width of 10 m was set as the reference width for correction, and then (3) and (4) that factor in dependence on displacement level were proposed for large-section cut and cover tunnels with a conversion width of more than 10 m to correct the ground correction coefficient $\rho$ for ground deformation coefficient [7]. Figure 3 shows the calculation results when $N$ value is 20 and the tunnel length $L$ is 20 m.
Fig. 3 Example of correcting vertical ground deformation coefficient [7]

Short term (variable action):

\[ \rho_{gk} = 1.0 \times \max \left( \frac{B_s}{B_r} \right)^{1 \over 2}, 1.0 \]  

Long term (permanent action):

\[ \rho_{gk} = 0.5 \times \max \left( \frac{B_s}{B_r} \right)^{1 \over 2}, 1.0 \]  

where \( B_r \): Reference conversion width (m), \( B_s \): Conversion width (m)

2.4 Performance verification for when diaphragm walls are used as part of the main tunnel structure

When designing a cut and cover tunnel where diaphragm walls are used as part of the main tunnel structure, the simple and easy separate-calculation method in which temporary retaining walls and the main tunnel structure are designed separately is often used. However, the separate-calculation method is not necessarily an appropriate method considering that diaphragm walls have been subjected to stress as a temporary structure before being constructed as part of the main tunnel structure.

On the other hand, the comprehensive calculation method, which factors in all construction processes involved from start to completion, is complex, must respect predetermined construction procedures and has other shortcomings. Given the above, a simpler comprehensive analysis method (Table 2), which offers roughly the same results as comprehensive calculations while factoring in residual stress during construction and is still not as complex as the comprehensive analysis method, was examined for applicability [8].

On new technologies, following the establishment of the cut and cover tunnel standards, a steel diaphragm wall with soil cement, shown in Table 3, was developed. Since 2006, the steel diaphragm wall has been increasingly adopted in construction projects including railway projects. Given the above, a project will be launched to analyze the rigidity, proof stress, nonlinear characteristics and waterproofing properties of the steel diaphragm wall with soil cement and propose a specific, standard performance verification method.

3. Conclusion

In this Perspective, general trends in design technologies for cut and cover railway tunnels are discussed centering on the discussions in the committee on the Design Standards for Railway Structures (Cut and Cover Tunnel). With cut and cover tunnels switching to the performance verification-based design, it is hoped that the introduction of new technologies will be facilitated and that durable and easy-to-maintain cut and cover tunnels will be constructed.

The design standards for the shield and mountain tunneling methods are currently being revised. Once available, the revised versions will be presented.

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