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Mechanical behavior of two kinds of prestressed composite linings: A case study of the Yellow River Crossing Tunnel in China

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ABSTRACT

This paper presents the mechanical behavior of two innovative prestressed composite linings in shield tunnels for water conveyance. The Yellow River Crossing Tunnel of the Middle Route Project of the South-to-North Water Division Project (SNWD) is adopted in this study as a case. Three-dimensional finite element models are established to analyse the stress distribution and deformation feature of the prestressed composite lining when the tunnel is under the completed segment assembly condition (CSAC), the completed cable tension condition (CCTC) and the design water pressure condition (DWPC). The calculation and analysis results reveal that the prestressed composite lining with rebars (Model R) has an obviously combined bearing capacity, and the rebar is the key factor influencing the capacity. The prestressed composite lining with membranes (Model M) has a relatively separated bearing capacity, because the membrane can play a significant role in preventing stress transmission between the segmental ling and the secondary lining. Full circular compression can be realized for the secondary linings of both Model R and Model M when the tunnel is under the DWPC. However, the load bearing mechanism of Model M is more concise than that of Model R, the secondary lining of Model M is more secure than that of Model R because of the full use of prestresses and materials, and the membrane is beneficial to anti-seepage. By contrast, Model M is more suitable for the Yellow River Crossing Tunnel.

1. Introduction

The prestressed composite lining is a kind of tunnel structure composed of an outer segmental primary lining and an inner prestressed secondary lining with circular anchor cables. The prestressed secondary lining can overcome the shortcoming of the small tensile strength of the concrete so that the concrete material can be fully utilized to withstand high internal pressures (Kang and Hu, 2005; Grunicke and Ristić, 2012). Therefore, this prestressed composite lining has more advantages over the ordinary double lining in load bearing capacity and anti-seepage capacity, and it is more suitable for application in shield tunnels with high internal pressures. According to the connection between the segmental lining and the prestressed lining, there are two types of the prestressed composite linings which are the prestressed composite lining with rebars (Model R) and the prestressed composite lining with membranes (Model M). The segmental lining and the prestressed lining of Model R are connected by rebars (Fig. 1a). The segmental lining and the prestressed lining of Model M are separated by membranes (Fig. 1b). At present, Model M has been applied to the Yellow River Crossing Tunnel of the South-to-North Water Division Project (SNWD) in China for the first time, while Model R has not appeared in projects.

The researches on the lining of the shield tunnel mainly focus on the monolayer segmental lining. The numerical models of the monolayer segmental lining mainly include the uniform ring model, multi-hinge ring model, beam-spring model, and shell-spring model (Lee et al., 2001; Ding et al., 2004; Do et al., 2013; Yang et al., 2014). In addition, three-dimensional finite element models are proposed to fully consider the three-dimensional effects of the segments (Blom et al., 1999). For the monolayer circular prestressed lining, it has been applied in some high pressure tunnels, such as the water conveyance tunnel of Geheyan Hydropower Station, the water conveyance tunnel of Tianshengqiao First Cascade Hydropower Station, and the desilting tunnel of Xiaolangdi Project in China. The common approach to considering the prestresses is to simplify them as a uniform radial pressure (Li et al., 2004). Since this simplified method cannot accurately simulate the nonuniform distribution of the prestresses along the circumferential direction and the spacing distribution of the anchor cables along the axial direction, it should be verified by three-dimensional finite element analysis or physical model experiments.

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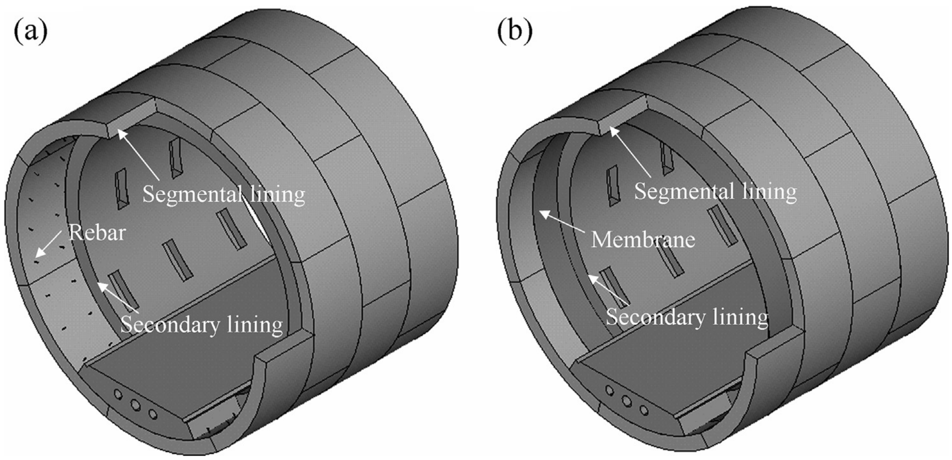

Fig. 1. Sketch of the prestressed composite lining: (a) Model R; (b) Model M.

The researches on the composite lining mainly focus on the ordinary double lining for shield tunnels. In the case of the double shell structure, the methods for computing the member forces of the secondary lining are generally divided into the bedded frame model method and the elastic equation method (ITA, 2000). A number of numerical calculations of the composite lining are based on the bedded frame model method. At present, the reported numerical models of the composite lining are mainly based on which the segmental lining is simulated by the two-dimensional beam-spring model or the three-dimensional shell-spring model, and the interaction between the segmental lining and the secondary lining is mainly simulated by springs, beams or contact (Murakami and Koizumi, 1987; Takamatsu et al., 1992, 1993; Zhang et al., 2001; Yan et al., 2015). This ordinary composite lining is mainly applied to railway tunnels and highway tunnels, and some research results reveal that reinforcing the coupling between the segmental lining and the secondary lining can improve the bearing capacity of the ordinary composite lining (Takamatsu et al., 1992, 1993; Zhang et al., 2001). However, for the prestressed composite lining, it is a combination of the segmental lining and the prestressed lining, and it is mainly applied to shield pressure tunnels. The distribution of the prestresses along the prestressed anchor cable length direction is not uniform, and the anchor cables are equidistantly distributed along the axial direction. In addition to the external load, both the prestress and the internal pressure are borne by the prestressed composite lining. Moreover, whether the segmental lining and the prestressed lining are separated by membranes or connected by rebars, both the membranes and the rebars have a significant impact on the stress transmission between the segmental lining and the secondary lining. Therefore, the structure form, load condition and stress transmission of the prestressed composite lining are all much more complex than the ordinary double lining. The numerical models and the research results of the ordinary double lining are not applicable to the prestressed composite lining directly.

The prestressed composite lining is an innovative and significant structure for the shield tunnel. This innovative technique is a desirable solution for the Yellow River Crossing Tunnel with characteristics such as poor geological conditions, high internal pressure, high anti-seepage requirements, deep buried depth, large cross section, etc. However, as it is applied for the first time in the world, there are few documented experimental, numerical or analytical results in the literature concerning this new type of the lining, and the mechanical behavior of the lining is still not clarified. Therefore, we investigate the mechanical behavior of the prestressed composite lining in a comprehensive way so that it could provide some references for the application of this typical lining in some other similar projects.

In this work, the Yellow River Crossing Tunnel is adopted as a case, and detailed three-dimensional finite element models are established to simulate the two kinds of the prestressed composite linings (Model R and Model M). The performance of each component of the prestressed composite lining and the interaction between the segmental lining and the secondary lining are analysed when the tunnel is under three working conditions. The first working condition is the completed segment assembly condition (CSAC) that the segmental lining is assembled and reaches stable states. The second working condition is the completed cable tension condition (CCTC) that the secondary lining concrete is poured and the prestressed anchor cable tension is completed. The third working condition is the design water pressure condition (DWPC) that the grooves are backfilled with concrete and the lining withstands the design water pressure. According to the analyses of the numerical calculations and the experimental results, the mechanical behavior of the two prestressed composite linings is presented and compared.

2. Case studied tunnel

The SNWD is the one of the most expensive project in China. This project consists of the Eastern Route Project, the Middle Route Project and the Western Route Project. For the Middle Route Project, it has been completed since December 12, 2014. Several generations of technical personnel have carried out a large amount of survey, planning, design and research work since the 1950s.

The Yellow River Crossing Project is a key project of the Middle Route Project of the SNWD, which is widely known as the most ambitious water conservancy project that crosses great rivers in the history of mankind. The Yellow River Crossing Tunnel is the largest individual project with the longest construction period, the most advanced technology and the most difficult construction in the SNWD. The total length of the Yellow River Crossing Tunnel is 3450 m, the excavation diameter is 8.7 m, and the design flow rate is 265 m^3/s. The longitudinal profile of the Yellow River Crossing Project is shown in Fig. 2.

The Yellow River Crossing Tunnel passes through soft soil and is constructed by the shield tunnelling method. In order to avoid large deformations of the excavation face, the precast segments are assembled timely to withstand the soil pressure and the external water pressure during the excavation. The internal water pressure in the centre of the tunnel is 0.51 MPa when the tunnel is under the DWPC. It is very important to prevent the high-pressure water from leaking out and to avoid seepage failure of the soil around the tunnel. If the internal water pressure is withstood only by the segmental lining, the segmental joints will be open sharply, resulting in water seepage. Therefore, a secondary lining is needed to improve the bearing capacity of the tunnel lining and to simultaneously improve the tunnel internal surface smoothing. As the prestressed concrete lining with circular anchor cables has advantages with respect to load bearing strengthening, high