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Numerical simulation of the uplift behavior of shield tunnel during construction stage

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Abstract

In this study, a new 3D numerical model that considers the circumferential joint, longitudinal bolt, grout pressure, jacking force and the constraint of shield on the linings is developed to derive deeper insights into the lining uplift behavior during shield tunneling. The numerical analysis is conducted using ANSYS, which is verified by a case history in soft soils. Revealed by both the measurements and calculation results, it is found that the lining uplift due to shield tunneling in soft soils can be divided into three stages: dislocation, stretch and steady deformation stages, respectively. In the dislocation stage, the lining deformation attributes principally to the dislocation deformation between neighboring linings. In the stretch stage, the lining deformation is mainly caused by the stretch deformation of circumferential joints. The major uplift is caused during dislocation stage. Thereafter, the impacts of shield-driving parameters including gradient of grout pressure, jacking force and pre-tightening force of longitudinal bolts on the uplift behavior are investigated by a series of parametric studies. The jacking force during segment preparation and assembly shows the most significant impact on the uplift of the tunnel, while the pre-tightening force of longitudinal bolts shows negligible impact. Finally, the control criterion for lining uplift related to the allowable dislocation and opening angle of circumferential joints is proposed.

Keywords: Shield tunnel; Lining uplift; Deformation; Numerical simulation; Control criterion

1. Introduction

The shield-driven method has been widely adopted for the construction of metro tunnels in soft soils due to its comparatively low impact on existing nearby structures. The gap between the tunnel lining and nearby soils occurs as a result of the separation between tunnel lining and the TBM tail. This is because the diameter of the TBM is larger that of the outer diameter of tunnel lining. This gap releases the constraint of nearby soils on the installed lining, which generates the available space for lining uplift or other displacements. Consequently, the gap is simultaneously filled with grout which needs a relatively long time for initial solidification. Meanwhile, since the TBM is continuously advancing, there are always certain lengths of tunnel linings located in the unsolidified grout. As a result, the buoyancy induced by unsolidified grout and hydrostatic pressure may be higher than the lining gravity, which leads to the lining uplift tendency.

The excessive lining uplift leads to local damage of the segments and leakage at the joints during shield tunnel construction, and therefore a deterioration in the safety and serviceability of tunnel structure. For instance, the common lining uplift of Ningbo Metro Line 1 in eastern China

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during the construction stage reached more than 30 mm, and induced local leakages and cracks in tunnel linings. However, the shield-lining-soil interaction mechanism and the lining uplift behavior is not yet fully understood. Hence, further understanding of the mechanism of lining uplift during construction stage is critical for shield tunnel in soft ground.

There are a number of geotechnical problems involved in shield tunnel construction. Extensive efforts have been made by researchers trying to reveal the shield tunneling-induced ground movement, including Fang et al. (1994), Park (2005), Chen et al. (2011b), and the stability mechanism of excavation face has also been revealed by Lee et al. (2006), Chen et al. (2011a), Chen et al. (2013). Meanwhile, the occurrence of frequent tunnel displacement in nearby constructions has been reported by Dolezalova (2001), Ng et al. (2013), Chen et al. (2016). The uplift behavior of tunnel linings during shield tunneling is also significant in practice, but has been commonly neglected.

In spite of the empirical model proposed by Zhou and Ji (2014), the mechanism of lining uplift behavior has yet to be investigated. A numerical simulation approach is favored for studying the mechanism of lining uplift. The two dimensional (2D) simulations by Zhang et al. (2013) appear inadequate, but are not capable of considering or revealing the three dimensional effect of tunneling and the longitudinal deformation of the tunnel. On the other hand, the in-situ behavior of shield tunnel construction can be simulated in a 3D model. The 3D numerical simulation presented by Kasper and Meschke (2006) considered such factors as the geological conditions, the shield machine, the tunnel lining, and the tunneling processes. The joints, however, were not simulated. The influence of joints was considered by Do et al. (2014). In these studies more attention was given to the ground behavior or the internal forces of the lining than the deformation of the tunnel lining. Mo and Chen (2008) presented a load pattern and simulated the practical tunnel structure in a 3D numerical model to study the structural behavior of the lining during the construction stage. Unfortunately, the displacement of the tunnel and the deformation (dislocation and stretch deformations) of the joints were not revealed. Therefore, few 3D numerical simulations which deal with the uplift behavior of linings during shield tunnel construction can be found.

In this paper, a new three-dimensional numerical model is developed and employed through ANSYS to study the mechanism of lining uplift. The segmental lining, circumferential joints, longitudinal bolts, grout pressure, jacking force, the constraint of the shield machine and the lining-soil interaction were taken into consideration in the model. The reliability of the numerical model was verified using the measured lining uplift of the Ningbo Metro Line 1 in eastern China. The characteristics of tunnel deformation and the internal force were investigated. Thereafter, the sensibility of shield-driving parameters was investigated by a series of parametric studies. Finally, a formula for evaluating the control criterion of lining uplift during shield tunneling was proposed.

2. Numerical model of lining uplift during shield tunneling

2.1. Mechanical model

As investigated, the lining uplift behavior is not affected by the advance rate of the shield machine according to Zhou and Ji (2014). A proper explanation is that lining uplift mainly develops during the standstill of the shield machine. This is because the time required for segment preparation and assembly is much longer than that for shield advancing. Fig. 1 depicts the state of the shield tunnel during the construction stage. The segmental linings are exposed to grout pressure and jacking force, as well as the constraints by the ground and shield tail. Loads and constraints applied on the tunnel linings are assumed to be a certain pattern (Fig. 2) due to the periodic process of shield tunneling. As presented in Fig. 2, the lining rings, circumferential joints, longitudinal bolts, grout pressure, the jacking force, and the constraints are all taken into consideration.

2.2. Segmental linings and longitudinal bolts

2.2.1. Segmental linings

Each lining ring of the shield tunnel was installed by several pieces of precast reinforced concrete segment. The longitudinal joint pattern has less effect on the normal displacement of the tunnel according to Mo and Chen (2008). For this reason, the segmental rings are considered uniform rings in this model. To reflect the impact of longitudinal joints, a reduction coefficient called the effective bending rigidity ratio η by Lee et al. (2001) and Teachavorasinskun and Chub-Uppakarn (2010) was employed in the uniform rigidity ring.

2.2.2. Longitudinal bolts

For simplicity, tensile and shear springs were applied to simulate the tensile and shear behavior of longitudinal

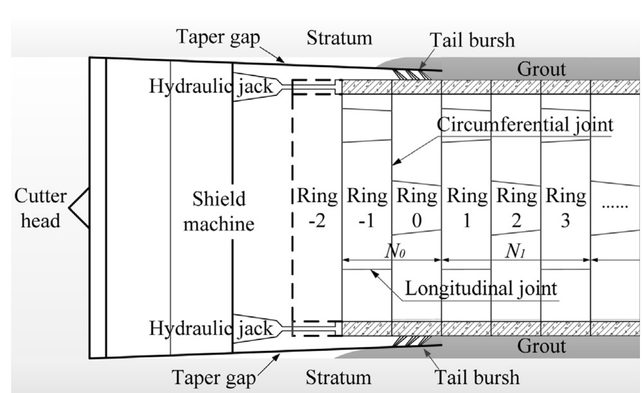

Fig. 1. State of shield tunnel during the construction stage.