Tunnelling and Underground Space Technology 82 (2018) 222–234

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Uplift resistance and progressive failure mechanisms of metro shield tunnel in soft clay

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ARTICLE INFO

Keywords:
Shield tunnel
Uplift resistance
Progressive failure
Transparent soil
Imaging techniques

ABSTRACT

In soft clay strata, a reliable design for disposing longitudinal uneven settlement of shield tunnels with grouting uplift technique requires the prediction of the uplift behavior. In this study, a laboratory model test system was developed to simulate the tunnel uplifting process by considering different burial depths of the tunnel. Transparent soils were prepared to model the typical clay, particle image velocimetry techniques were adopted to capture the internal continuous displacement field, and the load system was used to obtain the uplift resistance. During the uplifting process, the failure mechanism and response characteristics of the overlying soil were analyzed with different embedment ratios. According to the test results, two different resistance-displacement relationship curves are presented and described by four flag values. The pressure on the model tunnel is smaller than that on the pipe because there is no downward suction force underneath the tunnel during the uplift. Four different states are presented to describe the progressive failure mechanism of clay soil. First, the shear slip appears in the soil at the haunch of tunnel. Then, with the development of shear surface, the uplift resistance reaches the elastic limit. Soon afterwards, the uplift resistance reaches the peak; however, the complete shear band has not been formed. Finally, a complete shear band and an approximate vertical crack on the surface is observed, the overburden pressure reaches the residual uplift resistance, and the angle made by shear surface of soil wedge with the vertical plane are correlated with the embedment ratio of tunnel and the angle of internal friction of soils. Based on velocity fields, especially on the velocity direction, four-part failure mechanisms has been obtained.

1. Introduction

The differential settlement of tunnels constructed in soft deposits merits close attention during a metro system's operation (Zhou et al., 2016). Taking the Shanghai Metro Line No. 1 as an example, substantial differential settlement in the longitudinal direction was observed since it began operations in 1995. In 2010, the average cumulative settlement reached 111 mm, and the maximum cumulative settlement was 295 mm. The curvature radius of the settlement curves, which are less than 15,000 m and 1000 m, account for 40% and 3.52% of the upward line, respectively (Shen et al., 2014). The excessive longitudinal differential settlement of the tunnel has caused issues including structural dislocation, breakage, and leakage, indicating an adverse impact on the durability and bearing capacity of the tunnel structure (Zhang et al., 2017). The operational safety of a metro train cannot be guaranteed if the tunnel settlement exceeds the limit specified in the design standards (Huang et al., 2013).

In addition, when shield tunnels are constructed in the soft soil stratum, the axis of the tunnels are prone to deviation owing to the difficulty in construction parameter control and the large buoyancy during construction (Liu and Yuan, 2015). The tunnel segment rise of the Hangzhou Metro Line No. 2 and Ningbo Metro Line No. 1 were measured as 50 mm and 150 mm, respectively, during construction. (Ji et al., 2013).

If differential settlement or axis deviation of the tunnels occur, rectification of the tunnels is required to meet design standards. Some methods such as the microdisturbance grouting uplift technique have been used in Shanghai and several other cities in order to reduce the differential settlement (Zhu et al., 2016). Microdisturbance grouting uplift has been proven to be an effective restoration technique for shield

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https://doi.org/10.1016/j.tust.2018.08.038
Received 8 October 2017; Received in revised form 7 June 2018; Accepted 17 August 2018

tunnels through numerous engineering applications in soft deposit areas (e.g., Shanghai Metro Line No. 2, Hangzhou Metro Line No. 2, and Ningbo Metro Line No. 2 have been uplifted 11 mm, 8 mm, and 30 mm, respectively) (Wang and Wang, 2012; Zhu et al., 2016). Since the overlying soil pressure will change with the uplift of the tunnel, this may induce the deformation of the tunnel cross-section and even structural damage. Thus, it is necessary to assess the soil pressure on the tunnel during the uplifting process. However, there is a lack of effective methods for determining the overlying soil pressure.

In order to obtain the proper overlying soil pressure, the response characteristics of soil need to be predicted. However, current studies have mainly focused on approaches such as the lifting scheme (Wang and Wang, 2012) and lifting numerical simulation method (Tang and Zhao, 2008; You et al., 2011). The aim of the research described in this paper is to obtain the uplift resistance and response characteristics of overlying soil when uplifting a metro tunnel in soft clay strata, which can provide a basis for determining the overlying soil pressure during the gradual uplift of shield tunnels and designing reasonable grouting parameters. Hence, a small-scale model testing system with an image analysis technique was developed using transparent soils and the particle image velocimetry (PIV) technique combined with close-range photogrammetry in order to observe soil movement and deformation during tunnel uplift.

2. Previous investigations

Most research has focused on the microdisturbance grouting uplift techniques, including grouting parameters and technological processes (Wang and Wang 2012; Zhu et al., 2016). Research on the change in the uplift resistance and response characteristics of clay soils around the tunnel, especially the displacement field and progressive failure mechanism, are rarely reported during the uplifting process.

In another research field, the uplift resistance and corresponding failure mechanisms of soil during anchor, pipeline, and foundation uplift in sand were investigated using model test and theoretical study (Meyerhof and Adams, 1968; Ilamparuthi et al., 2002; Cheuk et al., 2007, 2008), which served as references for this study on tunnel uplift.

2.1. Uplift resistance

In the field of submarine pipelines, anchors, and foundations, a number of experimental and theoretical investigations have been performed by various researchers to predict the peak uplift resistance (PUR) (Davis and Rowe, 1982; Merifield and Sloan, 2006; Cheuk et al., 2008; Armaghani et al., 2015).

Armaghani et al. (2015) studied the effect of burial depth on the PUR of pipeline in loose sand based on 33 small-scale tests. Merifield and Sloan (2006) presented a rigorous numerical study based on plasticity theory to estimate the ultimate pullout load for vertical and horizontal plate anchors in friction soils.

However, most of the literature has focused on the PUR during anchor, pipeline, and foundation uplift in sand according to different assumed failure mechanisms and material behavior. At present, few literature has paid attention to the process of uplift resistance change.

2.2. Failure mechanism

Based on previous investigations of pipes, anchors, and foundations, conventional failure mechanisms are divided into three models as shown in Fig. 1: (a) vertical slip model, (b) inclined slip model, and (c) circular arc slip model.

In the vertical slip surface model (Majer, 1955) shown in Fig. 1(a), the uplift capacity is computed from the weight of soils within the failure surface above the pipe or anchor and the frictional resistance along the failure surface.

Mors (1959) proposed an inclined slip model with an apex angle (θ) equal to φ, where θ is the angle made by shear surface of soil wedge with the vertical plane, φ is the angle of shear resistance of soils, and the uplift capacity is assumed to be equal to the weight of the soils within the shear surface [Fig. 1(b)]. Clemence and Veesaert (1977) took the frictional resistance along the shear surface into account. Some research has indicated that the inclination of the shear surface is close to the soil dilation angle (White et al., 2001), while in other research θ was observed to be $\varphi/2$ (Ilamparuthi et al., 2002).

The half-cut model test (Balla, 1961) on mushroom foundations revealed a vertical rupture surface on the upper surface of the foundation, which curves outward and intersects the ground surface at approximately $45^\circ - \varphi/2$ with respect to the horizontal direction. This failure surface was simplified as a circular arc with radius $H/\sin(45^\circ + \varphi/2)$ [Fig. 1(c)].

Somewhat surprisingly, most researchers have focused on failure mechanisms in the limit state during the uplift of underground structures because they concentrated on the PUR. Cheuk et al. (2007, 2008) presented the four stages of the progressive failure mechanism when they studied the uplift resistance and failure mechanisms of pipes and plate anchors buried in sand. The main states are shown in Fig. 2. Each state is described as follows: (1) mobilization of PUR and formation of an inverted trapezoidal block while the shear zones curve slightly outward owing to higher dilatancy near the ground surface; (2) infilling and shear band formation; and (3) a flow-around mechanism near the pipe or localized flow-around mechanism without surface heave. They also found that peak angles of friction and dilation govern the geometry of the failure mechanism. However, this failure mechanism is only for sand.

2.3. Difference between uplift tunnel and other structures

Pipe uplift originates from upward buckling due to the increase in internal stress caused by temperature increase (Liu et al., 2013), while the uplift of anchors result from the upward tension transferred by a connected cable (Merifield and Sloan, 2006). During the uplift process of both pipes and anchors, the structure–soil interface is considered to be in complete contact. For a shield tunnel, the uplifting force originates from the tunnel's underlying stratum instead of the tunnel structure, as shown in Fig. 3. The tunnel–soil interface is separated by the grouting layer during the uplifting process. The study on pipe uplift shows that a downward suction force develops underneath the pipe in clay under undrained conditions during the uplift process, which has an impact on the failure mechanism of soils other than the uplift resistance (Das et al., 1994; Cheuk et al., 2007). However, suction force will not be generated because the tunnel–soil interface is separated by the grout layer during the tunnel uplift process. The uplift mechanism of a tunnel is significantly different from that of a buried pipe in existing research. Therefore, this study eliminates the suction force during model testing and presents a fully-equipped test method to study the uplift behavior of a tunnel during uplift.

3. Laboratory investigation

To avoid the boundary effect and for ease of obtaining the soil displacement field in the laboratory investigation, a small-scale model testing system was developed using transparent soils and the PIV technique. Through this system, the continuous displacement field inside the soils can be observed in a contact-less way (Ahmed and Iskander, 2012; White et al., 2003). The influence of the burial depth of the tunnel on the uplift behavior and progressive failure mechanism of soil were studied.

3.1. Tunnel uplift simulating method

Since this study focuses on the response characteristics of the overlying soil during the uplift process of the tunnel instead of the