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Analytical solution to steady-state temperature field with typical freezing tube layout employed in freeze-sealing pipe roof method

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ABSTRACT

Freeze-sealing pipe roof (FSPR) is an emerging auxiliary method in trenchless technology of underground engineering, which combines the advantages of Pipe-Roof Method and Artificial Ground Freezing method together. Based on practical engineering, a new typical freezing model of FSPR method with freezing tubes arranged inside jacking pipes is proposed in this paper, and then analytical solution to steady-state temperature field is obtained by transforming circular boundary condition to linear boundary condition with conformal mapping and superposition method. A comparison between the analytical results and numerical thermal results shows that the analytical solution is sufficiently precise for practical use. Temperature distribution of three characteristic sections gives an analytical validation for waterproofing performance and the results of field test bring a practical confirmation for the freezing effect of FSPR method. This paper enriches the theoretical research in steady-state temperature field of AGF and provide a reliable reference basis for FSPR design in future applications.

1. Introduction

Shallow Tunneling Method (STM), proposed in the 80s of last century and widely used in practical underground engineering, has become a mature construction technique for over 20 years (Wang, 2010). With the increasing density of underground engineering, carrying out a new project often encounter very harsh construction conditions, especially in urban built-up area. Nowadays, using one single auxiliary method alone, such as Pipe-Roof Method (PRM), often cannot meet the stringent engineering needs, the application of STM becomes more dependent on innovative development of auxiliary technique.

It is not surprising to see a tunnel with super-large cross section with the development of tunneling technology, however, when the construction site is in the city center, the difficulty will be completely different. Urban underground space is occupied by various existing building foundations, and little space is remained for a new tunnel, so sometimes tunnel alignment has to be changed from straight line to curve line. Beyond these, in groundwater-rich strata, how to deal with groundwater is also critical for tunnel excavation.

Among various auxiliary techniques, improved curved PRM (Zhang et al., 2013) can meet the requirements of bearing capacity, but curved pipe roof brings a new problem – failure of water sealing effect. The adjacent jacking pipes of traditional PRM are connected by sealing interlock, which is filled with waterproof material, when tunnel alignment is a curve, lock catch between two jacking pipes cannot guarantee the sealing performance. Therefore, Artificial Ground Freezing (AGF) method, as an effective temporary ground improvement technique in geotechnical interventions in soft soils, is proposed to work with PRM to deal with underground water. This new composite technique, "freeze-sealing pipe roof" (FSPR), which combines PRM with AGF, is especially suitable for shallow buried tunnels with super-large cross section built in water-rich soil, and employed for the first time in China during the construction of Gongbei Tunnel (Cheng and Liu, 2012).

In terms of freezing method used in FSPR, there have been some literatures or examples of similar methods at home and abroad. In Germany, using numerical method, Hamaguchi et al. (2005) studied the temperature field and the stress distribution of the pre-supporting method for a large cross-section excavation, which combined micro tunneling and ground freezing. Russian scholar Trupak (1954) concluded that steady-state analytical solution of freezing temperature field is precise enough for practical engineering application. In Japanese, Tobe N and Akimoto O (1979) calculated the analytical solution to multi-tube frozen temperature field with single-row freezing tubes. Then, Bakholdin (1963) improved this result, he obtained the analytical solutions to single-row-tube and double-row-tube steady-state frozen temperature field based on the theory of analogy between thermal and hydraulic problems, which were proved to be more exact after adjacent

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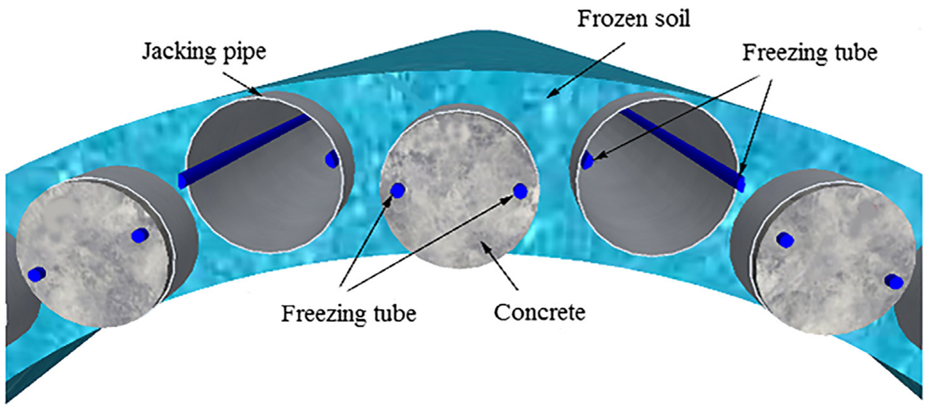

Fig. 1. Typical layout of the freezing tubes in FSPR.

frozen soil columns merged.

In China, Xiangdong Hu's research group, author of current paper, has done a lot of research on the design concept of the freezing method and the reliability of water sealing for the FSPR method through numerical simulation and model test. She (2013) carried out a preliminary study of the freezing scheme in the FSPR method based on unsteady conjugate heat transfer theory. Hu and Fang (2014) considered the influence of airflow on freezing by introducing the conjugate heat transfer theory and thus furthered the research on FSPR. Wang (2013) analyzed the mechanical properties of steel pipe-frozen soil composite structure by laboratory test. Hu et al. (2018) studied the large-scale physical test on frozen status in FSPR. With respect to analytical solution, Hu's group gradually improved these existing analytical solutions and did lots of research for better application of these results in practical use (Hu et al., 2016). Besides, new calculation method like superposition of thermal potential (Hu et al., 2016) and boundary separation of harmonic function (Han, 2015) were proposed, and more analytical solutions were obtained, they include single-row-tube steady-state temperature field with different temperature of freezing tubes (Hu et al., 2013), analytical solution to generalized double-row-tube (Hu et al., 2015) and generalized triple-row-tube (Hu and Wang, 2012) steady-state temperature field. For freezing tubes arranged in circle, there are also some results (Hu and Han, 2015). However, analytical solution to steady-state temperature field of FSPR is still not available and this brings many difficulties in practical application.

In this paper, based on FSPR method, an analytical result of circle-tube freezing model with non-equal tube spacing is obtained. Then, a comparison between analytical results and numerical results is done which gives a credible verification for the analytical solution. At last, through the field test of FSPR method used in Gongbei Tunnel, we provide a practical validation for water sealing performance between two adjacent jacking pipes. Although this paper gives an exact analytical solution to temperature field of typical FSPR method, it is necessary to note that, this solution needs to be used cautiously when the shape of tunnel section is irregular or there are more than one circle of freezing tubes.

2. Engineering background and model simplification

2.1. Engineering background

FSPR is a combination of PRM method and AGF method and is now becoming more and more popular in underground engineering, it can reliably mitigate risks of damage of existing structures during tunnel construction with shallow covering soil in sensible urban areas and efficiently control the groundwater during excavation. According to whether frozen curtain play a role of bearing structure, two well-known practical applications of FSPR are Brandenburger Tor subway station excavation construction of underground line U5 in Berlin metro system extension project (Speier and Klönne, 2009) and Gongbei tunnel in Zhuhai connecting line of Hong Kong-Zhuhai-Macao Bridge (Cheng et al., 2013).

In U5 Line construction, 30 steel jacking pipes form a 90-m pipe roof, which play a role of bearing structure together with frozen curtain. The diameter of each pipes is Φ1610 mm, four freezing tubes are installed in jacking pipes for circulating cold brine. Among all jacking pipes, some of them are designed to remain in soil, so they are filled with concrete for better thermal conductivity and bearing capacity. In Gongbei tunnel, the pipe-roof design consists of 36 jacking pipes with a diameter of 1620 mm, and these pipes are also filled with concrete every other one during tunnel excavation. Three kinds of freezing tubes are arranged in these steel pipes to control the development of frozen curtain. Japanese scholars once did some researches on the coordinate deformation ability of these composite structure with "jacking pipes + freezing", but the freezing effect of FSPR has not been studied yet.

From these two applications of FSPR method, we can easily find some typical features in the design of jacking pipes and freezing tubes. The biggest characteristic of FSPR is that all freezing tubes must be installed inside steel jacking pipes due to curved tunnel alignment, which is different from previous freezing project. Moreover, seen from the entire tunnel section, spacing between adjacent freezing tubes is not equal, the freezing tubes layout of FSPR is distinguished from traditional arrangement, so the temperature field and freezing effect with this form of freezing tubes arrangement need some further research. The typical arrangement of FSPR is shown in Fig. 1.

2.2. Model simplification

As mentioned above, the number of freezing tubes and the shape of tunnel section are different from others, for generalizing the common characteristics of FSPR, some simplification for practical engineering is necessary. Among all kinds of freezing tubes installed in jacking pipes, freezing tubes in solid pipes filled with concrete and those in empty pipes are mainly used for brine circulation during freezing process, these two kinds of freezing tubes are also the object of this paper to explore the analytical solution of frozen temperature field distribution. Other simplifications also include:

(a) The actual three-dimensional heat conduction problem can be simplified as a two-dimensional one in that the longitudinal length of a freezing tube is by far greater than its diameter and its surface temperature actually changes very slowly in the longitudinal direction.
(b) Simplify irregular shape of tunnel cross section as a circle shape, all the freezing tubes are considered to be arranged on a same circle, and ignore the small offsets in the radial direction of the tunnel.