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Minimum ground pre-freezing time before excavation of Guangzhou subway tunnel

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Abstract

Artificial Ground Freezing (AGF) has been in use for more than a century. However, there are few published papers concerning about thermal and mechanical calculation and analysis of AGF. Especially, in the practical project, when other factors such as freeze temperature, quantity and spacing of freeze pipes, are same, the ground pre-freezing time affects the project cost as well as the strength of frozen wall. So, in this paper, a subway double-line tunnel in Guangzhou constructed by AGF is taken as an example. At first, a numerical model for thermal and mechanical analysis is proposed. Then, based on this model, the surface settlements are calculated and compared by using finite element method (FEM) when the ground pre-freezing time are 60, 50, 40 and 30 days, respectively. According to the criteria of code that the maximum surface settlement is less than 30 mm, a minimum pre-freezing time could be selected. At last, under the condition of this minimum pre-freezing time, the temperature fields, stress fields and displacement fields at every excavation step are calculated and analyzed. The safety of frozen earth wall is also evaluated by applying long-term strength equation of frozen soil.

Keywords: Artificial ground freezing; Subway tunnel; Pre-freezing time; Surface settlement

1. Introduction

The first recorded application of AGF was on a mine-shaft project near Swansea, South Wales, in 1862, and it has also been in use for more than 40 years in China. AGF is a versatile technique that involves the use of refrigeration to convert in situ soil pore water into ice. The ice becomes a bonding agent, fusing together adjacent particles of soil or blocks of rock to increase their combined strength and make them impervious to water seepage. Excavation and other work can then proceed safely inside, or next to, the barrier of strong, watertight frozen earth (Andersland and Ladanyi, 2004). Some engineering experiences show that it is very effective to provide ground support, groundwater control, or structural underpinning during construction. And the frozen wall, which is constructed prior to excavation, for practical purposes, eliminates the need for sheeting of the earth, site dewatering, soil stabilization, or concern for movement of adjacent ground. However, despite the fact that AGF has been well known for many decades in engineering, the theoretical aspects of thermophysics and soil mechanics have not been solved. And the present researches concerning about AGF have only concentrated on engineering technique and test instead of

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theoretical calculation and analysis up to now. For example, H. Wind (1979), Xiao et al. (2002) and Zhou et al. (1999) discussed the technique and principle of AGF; Yu et al. (2005) analyzed briefly monitoring temperature in frozen wall during construction; Wang et al. (2004) did an experiment to research variable regularity of temperature field during freezing stage. Nevertheless, as is generally known, the behaviors of frozen soils vary according to their properties and temperature. So, when the AGF is about to be applied to design and construct a tunnel or other, the engineers should clearly know that how long need the ground be frozen at least before excavation, and what are temperature distribution and mechanical state in the frozen soil and unfrozen soil during construction. Unfortunately, in practice, it is not the case; the engineers often make a design according to previous experiences instead of detailed theoretical analysis. In order to solve the above questions and provide theoretical references for the engineers, an example from a subway double-line tunnel in Guangzhou is employed to analyze the minimum pre-freezing time as well as the thermal and mechanical states in the soils during every excavation step. The analysis steps and methods are described as following.

(1) Because the temperature field of AGF is a problem of transient heat transfer with phase change, moving boundary, internal heat source and complex boundary conditions. In addition, there are heat convection between the air and the opening surface of the tunnel and heat of hydration of cement. So it is not possible to get an analytical solution for this problem. But the numerical method could solve this problem completely. Firstly, based on the governing differential equations of transient temperature field with phase change and heat generation of freeze pipes, the temperature field of every excavation step is computed and analyzed by finite element method (FEM). Then, according to the distribution feature of temperature field and corresponding mechanical parameters under this temperature field, the stresses and displacements of frozen soil and unfrozen soil at corresponding excavation step are also analyzed through using creep constitutive model for frozen soil and elastoplastic constitutive model for unfrozen soil.
(2) By using this model, the surface settlements are calculated and compared by using FEM when the ground pre-freezing time are 60, 50, 40 and 30 days, respectively. According to the criteria of code that the maximum surface settlement is less than 30 mm, a minimum pre-freezing time is decided.
(3) Under the condition of this minimum pre-freezing time, the temperature fields, stress fields and displacement fields at every excavation step are calculated and analyzed. The safety of frozen earth wall is also evaluated by applying long-term strength equation of frozen soil.

2. General description of the subway double-line tunnel in Guangzhou

This study project consists of an arch-shaped 11.8-m-wide double-line tunnel in Guangzhou, China, and the tunnel is approximately 147.8 m in length, 9.0 m beneath land surface. The subsurface conditions consist of fill, which depth is 1.65 m, and beneath this material is a thick stratum of clay with varying amounts of silt and sand. What's more, the underground water level is very high. In addition, there is a highway and a bridge above the tunnel. Therefore, when the tunnel is constructed, the surface settlement induced by tunnel excavation should be controlled strictly. Except that a reasonable

Fig. 1. The photos of freeze process and freeze pipes.