Simulation of Heat Transfer During Artificial Ground Freezing Combined with Groundwater Flow

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Abstract

The artificial ground freezing (AGF) method has been widely used in civil and mining engineering. Its principle is to circulate a fluid refrigerant (ca. -30°C) through a pre-buried pipe network in the subsurface in order to form a freezing wall for construction strengthening. The knowledge of the in-situ temperature distribution is the key factor with respect to the development of the freezing wall. The main physical process is a transient heat conduction phenomenon with phase change. In common cases, the temperature change is only considered as a heat conduction process. However, with groundwater of high flow velocities, the influence of the water-ice phase change on the flow properties should not be neglected. In this work, we performed a case study of a strengthening project of a metro tunnel with AGF method, considering the influence of groundwater flow.

With the simulation software COMSOL Multiphysics®, a 2D cross section of a horizontal AGF project (Figure 1) is selected and a numerical model is set up, which is based on full coupling of temperature and flow fields by using Darcy's Law and Heat Transfer in Porous Media physical interfaces. Firstly, the Darcy velocity is selected as a coupling variable and linked to the temperature field. Subsequently, as the pore water gradually turns into ice, the permeability in freezing zone is decreased. At this phase, we introduce a variable of effective hydraulic conductivity which can be described by a function of temperature change. The energy conservation problem during freezing phase change is solved by apparent heat capacity method and the related parameter change is described by a step function. The corresponding mesh is generated through automatic remeshing (Figure 2). This model is validated with in-situ temperature observations.

The results demonstrate the temperature and groundwater flow field at various times. Figure 3 shows one of the results on the 35th day as an example. Concluded with other results at different times, the temperature contour maps combined with groundwater flow velocity (black arrows in Figure 3) indicate that the freezing wall appears in an asymmetrical shape as the horizontal groundwater flow is normal to the axial of the tunnel. Along the groundwater flow direction, freezing wall forms slowly and on the upstream side the thickness of the freezing wall is thinner than that on the downstream side. The closure time of the freezing wall increases at the middle of the both up and downstream sides. The average thickness of the freezing wall on the upstream side is mostly affected by the groundwater flow velocity. With the successful validation of this model, this numerical simulation could provide guidance in this AGF project in the future.

Reference

[1] R. L. Harlan, Analysis of Coupled Heat-Fluid Transport in Partially Frozen Soil, Water Resources Research, Vol. 9, p. 1314 (1973)

[2] J. M. McKenzie et al., Groundwater Flow with Energy Transport and Water–Ice Phase Change: Numerical Simulations, Benchmarks, and Application to Freezing in Peat Bogs, Advances in Water Resources, Vol. 30, p. 966 (2007)
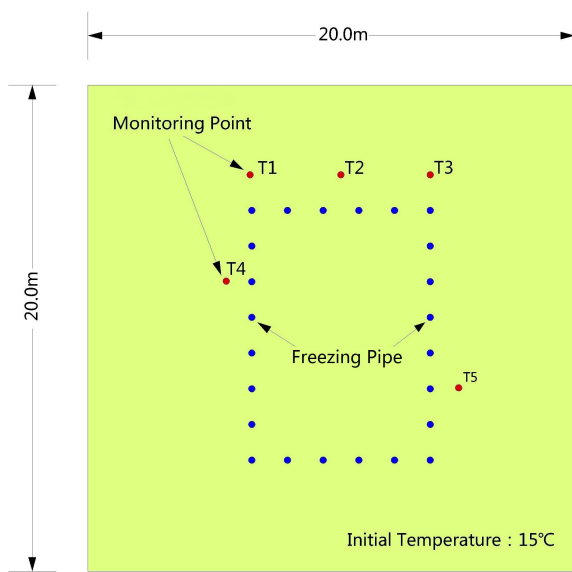
Figures used in the abstract

Figure 1: The geometry of cross section from horizontal freezing engineering.

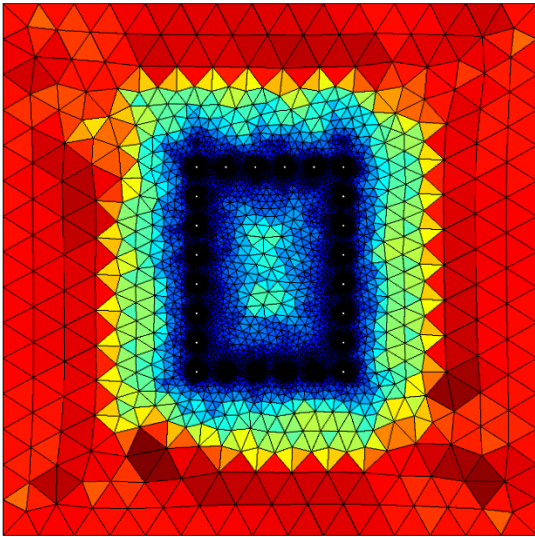**Figure 2**: The mesh generation calculated by automatic remeshing.
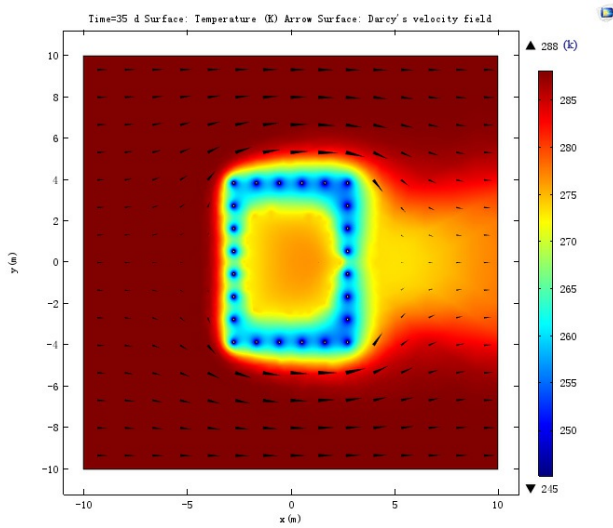

Figure 3: The calculation results of temperature and seepage field at 35th day.