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Experiments and simulations of underground artificial freezing with the use of natural cold resources in cold regions

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ABSTRACT

This study proposes an artificial freezing method that consumes low energy by combining air-cooling and a conventional method. The method fully utilizes a naturally low air temperature in a cold region, which reduces freezing costs and avoids environmental influence. A refrigeration experimental platform is designed to study the refrigeration effects of natural cold sources. A mathematical model is built to analyze the evolution of temperature. And the temperature field was simulated by software——ANSYS. The simulated results match the experimental data well and verify the feasibility of the proposed method. Moreover, air-cooling economy and conventional refrigeration are analyzed. The running cost and power of the air-cooling method are respectively reduced by 52% and 53.4% when compared with the values for the conventional method. This approach effectively reduces refrigeration power load and project cost, consumes low energy, and is environment friendly. This study can thus serve as a reference for new ideas on underground artificial freezing.

1. Introduction

An artificial freezing method is an approach used to build a temporary frozen wall for underground excavation under complicated hydrogeological conditions. The method enhances soil stability, decreases deformation, and partition groundwater [1]. This approach is used to excavate vertical shafts, subway tunnels, underground frozen soil, and deep foundation pits.

Artificial freezing has gained considerable attention for satisfactory water tightness and environment-friendly characteristics [2]. The method is irreplaceable in urban underground engineering and loose water-bearing strata construction [3].

The artificial freezing method has been applied for more than 150 years. A British engineer, South Wales, first used artificial freezing technology to reinforce soil during the construction of a building foundation [4]. In 1880, German engineer F.H. Poetch proposed the principle of the freezing method, for which he obtained a patent [5]. By 1990, the use of artificial freezing in mine construction has been accounted for more than 60 times [6]. After more than a century, the method has been widely used in coal mines, tunnels, subways, and building foundations [7].

The freezing method was successfully utilized for subway engineering across the Seine bottom in France in 1906, for the uneven settlement adjustment of a 26-floor building in Brazil in 1942, for a canal tunnel project in Britain in 1968, and for a shaft installation project for water intake under a lake in the United States in 1973 [8]. Since the 1990s, artificial freezing has been widely applied worldwide to achieve different engineering purposes. These projects include underground support treatment below water level in a subway construction in Valencia, Spain [9], a frozen soil cofferdam (diameter = 6.1 m) in a large and deep tunnel in Milwaukee, United States [10], an underground power transmission tunnel project in Nagoya, Japan [11], and sewage pipe railway engineering across Germany [12].

The artificial ground freezing technique was applied as temporary soil improvement [13]. In 2004, the method was successfully used to form an underground frozen wall in an oil shale for an in-situ underground mining engineering project [14–20].

However, the high cost of freezing construction has always been a limitation [21]. Freezing engineering construction costs generally include two aspects: freezing hole construction and freezing refrigeration. Freezing refrigeration energy comes from electricity. A large or medium-sized freezing project needs approximately 300 kV A to 1000 kV A of power, and the refrigeration electric load should always be above 300 KW [22]. A high refrigeration electric load is in conflict with the city power peak, especially in urban

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construction [23]. Therefore, refrigeration electric load should be reduced, and project costs should be decreased.

The utilization of natural cooling sources has a long history. The use of such natural cooling sources on refrigerated food can be traced back to Ancient Greece and Iran, where ice was taken from the river and kept in sawdust for use in winter [24]. In China, the use of natural cooling sources dates back to the Shang and Zhou dynasties [25].

Natural cold sources were used to make waterproof curtains for gold mining in the eastern Siberia Yeniseian forest in the early 18th century; the people in this area were the pioneers in applying natural cold sources to mine construction [26].

Over the last two decades, scientists from Canada, Japan, the United States, and China have been studying cool storage systems for seasonal natural cold sources; these systems have been made available in the market and have brought economic benefits [27–36]. Moreover, at least 30 countries are located in the northern hemisphere, with more than 600 million people living in high latitudes (e.g., Canada, the United States, the Scandinavian Peninsula, Iceland, Greenland, Switzerland, Russia, Japan, and China). These people experience the cold during the winter [37]. Therefore, the full use of natural resources in these areas for engineering purposes significantly reduces artificial freezing cost and creates a friendly environment.

Inspired by mixed refrigeration mode [38], in this study, a novel artificial freezing method that uses low air temperature as a refrigerating medium in cold regions is investigated. The proposed method is combined with a refrigeration unit to reduce freezing costs and environmental influence. Moreover, the method effectively reduces the refrigeration power load and project costs, consumes low energy, and employs an environmental protection method. Several experiments and engineering projects verify the underground freezing effect of the conventional refrigeration unit. However, no research has been conducted on underground freeze-making through air-cooling, which can provide a comprehensive understanding of the underground freezing process. Thus, this study aims to determine the feasibility of air-cooling. A refrigeration experimental platform is designed to study the refrigeration effects of natural cold sources. The experimental results prove that the method has a significant refrigeration effect. An ANSYS model is built to analyze temperature evolution. The simulated results match the experimental data well, which verifies the correctness of modeling. Moreover, the experiment costs are analyzed to validate

Fig. 2. Photograph of the experimental platform.

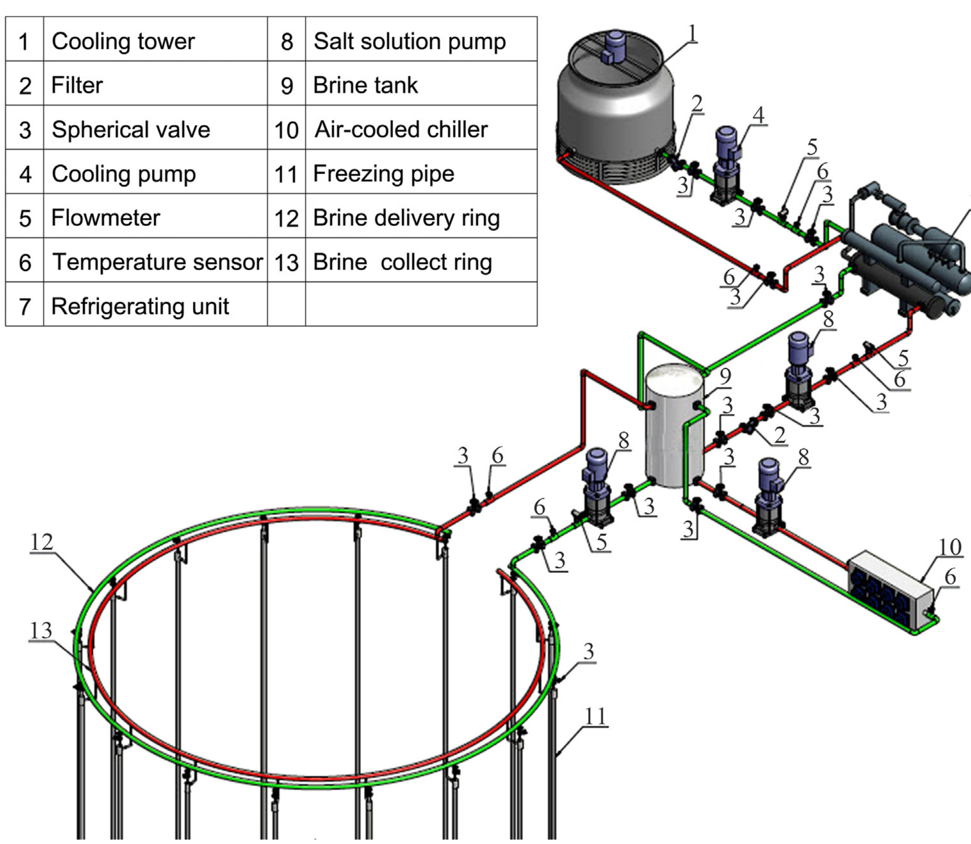

Fig. 1. Experimental platform scheme.