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Artificial ground freezing for underground construction – a brief review of the theory, practice and challenge

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Since Artificial ground Freezing (AGF) appeared in the 1880s in the mining sector in Europe, it has been used for various construction applications worldwide. In recent years, it has been increasingly popular in urban projects due to its versatility and applicability to complicated site conditions. So far, it has been used to stabilize substrata to nearly 1,000 m below the ground surface, which is considered not possible for many other ground improvement technologies. Due to the growth in field applications, the practice and theories related to AGF have become more mature in the most recent two decades. The improvement in understanding of this topic is a result of lessons that have been learned through numerous projects, as well as a variety of comprehensive studies that have been completed. This paper reviews the existing practice, the recent development on AGF and the challenges of AGF.

KEYWORDS

artificial ground freezing (AGF), soil improvement, excavation, underground construction, tunnel

1 Introduction

Artificial ground freezing (AGF) is a soil stabilization technique, which involves removing heat from the ground through circulation of a chilled liquid to convert pore water into ice (Harris, 1995; Jones et al., 1982; Schmall and Braun, 2006). The ice in the pores of soil mass bonds soil particles to form a soil-ice composite that temporarily stabilizes soil, cuts off water flow, and provides support for excavations (Hashemi and Sliepcevich, 1973; Lacy and Floess, 1988; Sanger, 1968). The impervious nature of ice also makes AGF suitable for temporarily immobilization of various species of contaminants, including radioactive materials (International Atomic Energy Agency, 2006). In summary, AGF is a very useful technology for many applications even though it is not among the most used ground improvement technologies. The first reported use of Artificial Ground Freezing (AGF) for underground construction occurred in 1862 in Swansea, South Wales, where a mineshaft was constructed by circulating chilled brine through tubing sunk into the ground (Harris, 1995). This concept was later patented in 1883 by German engineer F. H. Poetsch to prevent water ingress in Belgian coal mines (Harris, 1995; Schäfers and Hab, 2005). The principles outlined in Poetsch's patent remain relevant to modern projects. Since the 1880s, AGF technology has been implemented at increasing depths in various countries. Germany achieved a penetration depth of approximately

600 m, Canada reached 900 m in the 1950s, and England reached 975 m in the 1970s (Harris, 1995; Hass, 2006). China has also reported multiple AGF projects with depths exceeding 800 m, with the deepest being 990 m in Shanxi Province (Wu et al., 2020; Zhang et al., 2012). These deep applications are primarily used for sinking mining shafts and open pits. In China alone, the total length of shafts constructed using AGF reached 227 km by 2010 (Zhou et al., 2022). The first urban underground application of AGF was in 1886 in Sweden for a pedestrian tunnel (Kinoshita, 1982). Since then, AGF has been widely used in urban transportation systems, especially in densely populated coastal cities. In recent years, China has extensively employed AGF for its inner-city transportation projects, initially as a supplement to jet grouting and then increasingly as the preferred method. By 2016, more than 700 urban underground AGF projects had been completed in China, mostly in large coastal cities (Zhou et al., 2022).

2 Principles and practice

The working principle of AGF is relatively simple. The heat energy of underground soil and water is extracted by circulating cooler liquid so that ice is formed to create frozen soil. The most important component of AGF is the freezing system, which circulates low temperature liquid to exchange heat with subsurface soil. The original patented prototype was a refrigerant-brine system, which includes two closed loops: cooling and circulation, which work independently (Alzoubi et al., 2020). The cooling system functions like a refrigerator, which lowers the temperature of the brine (typically calcium chloride). Then the brine is circulated through buried tubes to cool the soil. The heat exchange of two loops is achieved to lower the brine temperature after it returns from circulation. For the cooling system, the used refrigerant includes Freon, ammonia, R22 and fluorine (Zhou et al., 2022; Zhou et al., 1997). So far, the refrigerant-brine system can lower the brine temperature to −22°C to −35°C (Harris, 1995; Zhou et al., 2022). In contrast, an open loop cooling system uses liquid nitrogen (LN) to extract heat from soil (Alzoubi et al., 2020). The returning nitrogen gas is released to the air. Such a system can lower the soil temperature to approximately −100°C, which turns pore water into ice immediately. The idea of LN for AGF came out around 1960s and soon rapidly became an alternative cooling choice (Jessberger and Jagow, 1988; Zhou et al., 2022). Compared with refrigerant-brine cooling system, LN system is safer because nitrogen is harmless. For both cooling systems, once frozen soil mass is formed it is typical to maintain the temperature between −30°C to −15°C to save energy (Chang and Lacy, 2008).

Theoretically, this method should be applicable to all soils and rocks as long as there is sufficient water and water flow is insignificant (Harris, 1995). According to Harris (1995), Thorburn and Littlejohn (1992), and Karol (1990), the AGF is probably the only ground improvement method that can be used for any type of soil and rock. As a matter of fact, AGF has been successfully used from very soft clay to rock (Russo et al., 2015; Vitel et al., 2016b; Zhou and Tang, 2018). Another outstanding advantage of AGF is great treatment depth, which is typically a few hundred meters and can be as deep as 1,000 m (Harris, 1995; Zhou et al., 2022). The deepest jet grouting and deep soil mixing can reach 150 m, while stone columns and rammed aggregate columns typically cannot be more than 20 m (Schaefer et al., 2017). The disadvantage of AGF lies in two aspects: temporary and costly. The soil will thaw shortly after the circulation pauses. The cost of AGF includes drilling, installation, freezing and maintaining temperature, which could be significantly higher than other methods.

3 Practice, research and development

AGF was initiated from mining excavation and construction, which was then used in many other underground and above ground construction. Particularly, after horizontal drilling and inclined drilling become possible, AGF gained significant attention in tunneling, open excavation, underpinning, gap filling, slope stabilization, cofferdam, and permafrost preservation (Harris, 1995; Jones et al., 1982; Thorburn and Littlejohn, 1992; Viggiani and Casini, 2015). In 1997, AGF was used with the assistance of horizontal drilling to build a tunnel of metro line in Beijing (Qiao et al., 2004). In that project, horizontal tubes were installed to create a vaulted portion to prevent the saturated running sands from collapsing. Li (2007) reported extra-long horizontal freezing of 140 m when building metro line in Guangzhou, China. A few years later, Su and Su (2014) reported an inclination angle of 14° of AGF in a coal mining application. The field success and advance in construction techniques have greatly promoted the usage of AGF. In addition to the advance in construction technology, there is a noticeable advance in materials. For example, non-metal pipes has been developed and used in AGF so they can be left in place when tunneling machine cutting through frozen soils (Zhou et al., 2022).

Alongside advancements in construction, extensive efforts have been made to understand the basic phenomena and fundamental theories underlying AGF. Initially, AGF practice was based primarily on freezing kinetics, including thermal conduction, diffusion, and phase change. However, it gradually became clear that AGF involves more complex physical processes, such as nucleation and crystal growth, pore water movement, and soil-water interactions. Shackelford (2000) described that the initiation of freezing begins with unstable clusters of water molecules when the temperature drops below the freezing point, T_f. For pure water, T_f is approximately −40°C according to (Fletcher, 1970). However, in natural environments, the presence of foreign surfaces, particles, and ions causes the freezing temperature, T_f, to be around 0°C. In soil, pore water is bound to surfaces of soil particles by chemical bonds and electrostatic forces, with bonding strength decreasing as the distance from the particle surface increases. Consequently, the freezing of pore water starts from the center of the pores and gradually progresses to soil particle surface (Lackner et al., 2005). Willams (1988) studied ice formation and the percentage of unfrozen water in total pore water at different temperatures, summarizing the results into non-linear relationships depending on soil types, as shown in Figure 1. The study found that only 1% of pore water in sand remains unfrozen when the temperature drops below 0°C, but about 5% of water in silt and 8%–20% in clay remains unfrozen at −5°C (Harris, 1995; Willams, 1988). These findings provide fundamental theories to design and analyze the thermal problems related to AGF (Harris, 1995; Lackner et al., 2005; Lackner et al., 2008).

When supporting excavation, the strength of the formed soil-ice composite is a crucial design parameter. It has long been established that the strength of frozen soil is a function of temperature. Generally, compressive strength increases as temperature decreases,

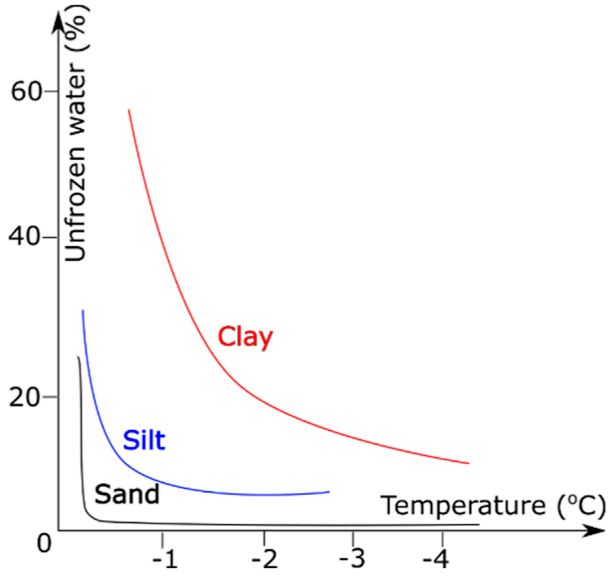

FIGURE 1
Unfrozen water content as a function of temperature for different types of soil [modified from Willams (1988)].

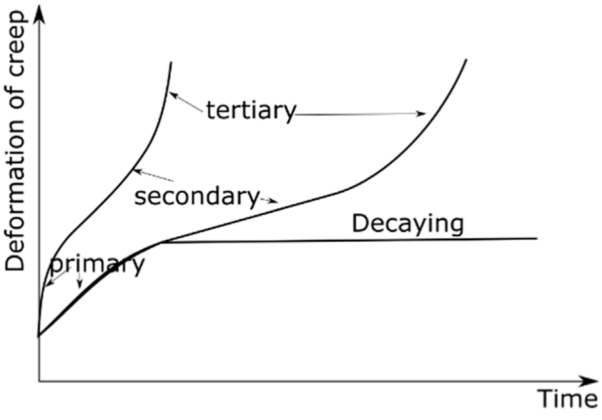

FIGURE 2
Binary model for frozen soil creep [modified from Wang et al. (2019)].

and clay soils are more affected by temperature changes than sandy soils (Haynes and Karalius, 1977; Shastri et al., 2021; Tsytovich, 1975). The creep behavior of frozen soil became a focus for engineers with the study of bearing capacity foundations on frozen ground (Parameswaran, 1987). Extensive analytical and experimental research has been conducted to understand this behavior (Fish, 1980; Ladanyi, 1972; Ladanyi, 1983). Early studies indicated that the creep behavior of frozen soil is similar to that of other materials like polymers and metals, with primary, secondary, and tertiary phases based on strain rate (Ladanyi, 1972; Zhu and Carbee, 1983). However, further research revealed that frozen soil might experience strength attenuation under loads, differentiating its creep behavior from other materials (Wang et al., 2019; Yao et al., 2017). Wang et al. (2019) proposed a binary model (Figure 2) to describe the creep behavior of frozen soil, accounting for both non-decay and decay scenarios. Considering strength decay significantly alters the secondary creep phase, impacting AGF applications.

Other significant developments include thermal models accounting for high-velocity water flow, failure criteria of frozen soil considering creep and temperature, constitutive models for frozen soil, temperature distribution in frozen soil, ice lens and soil interaction, and the impact of ice formation on soil structure (Huang et al., 2018; Lackner et al., 2005; Lackner et al., 2008; Liang et al., 2022; Marwan et al., 2016; Vitel et al., 2016a; Vitel et al., 2016b; Xie et al., 2015; Zhao et al., 2023). Advancements in understanding over the past few decades have not only made designs more reliable and construction safer but also resulted in significant energy savings.

4 Conclusion

As AGF becomes more and more popular, it has been used in more and more applications; consequently, more challenges emerge (Harris, 1995; Zhou et al., 2022). Some of the challenges lie in lacking of a full understanding of the problem, for example, frozen soil behavior under cyclic or impact loads, and consolidation induced by soil frozen. Whereas others are due to the complexity of the site that makes uncertainty unknown (Liu et al., 2015; Zhou et al., 2022). Therefore, failure of AGF is not uncommon (Li et al., 2015; Zhou et al., 2022). Shuster (2000) reported more than one hundred problems that have plagued AGF projects, which are related to design, construction, installation, maintenance. Therefore, it can be concluded that AGF has become more mature nowaday but further studies are needed to improve this technology, particularly, improve the understanding of the uncertainty under complicated, large-scale projects.

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HM: Conceptualization, Resources, Writing–original draft, Writing–review and editing. JH: Conceptualization, Writing–review and editing. DJ: Conceptualization, Writing–review and editing.

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