

The geological conditions in both China and Poland are complex and diverse, with some areas often located in seasonal frozen soil zones, as shown in Figure 1. The freeze-thaw effect in these regions significantly impacts the soil's structural integrity, shear strength, permeability, and thermal conductivity. Such changes often lead to instability, sliding, or flow of frozen soil slopes under freeze-thaw cycles. Thus, reinforcement measures, such as soil reinforcement, are necessary for slopes in frozen soil regions [2,3]. By incorporating reinforcement materials, e.g., geogrid, into the soil, the friction and interlocking effects between the two can significantly enhance slope and embankment stability.

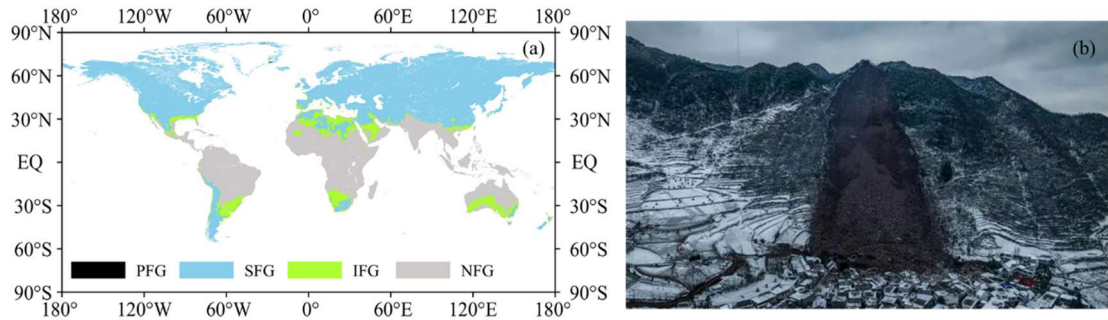


Figure 1. (a) Global permafrost zone map [1] and (b) Slope sliding caused by freeze-thaw effects (PFG: Permafrost Zone, SFG: Seasonal Frozen Ground Zone, IFG: Intermittent Frozen Ground Zone, NFG: Non-Frozen Ground Zone)

In permafrost regions, geogrid, as a commonly used reinforcement material, face significant challenges in performance under seasonal freeze-thaw cycles. Freeze-thaw cycles cause significant expansion and contraction of the soil, intensifying stress concentration at the soil-reinforcement interface, which in turn affects the overall mechanical performance of the reinforced system. This stress concentration not only weakens the long-term stability of reinforced soils but also accelerates interface degradation during the thawing of frozen soils, leading to structural failure [4]. Furthermore, this performance degradation imposes higher demands on the design, construction, and maintenance of projects in cold regions, while also causing significant economic costs and potential safety hazards [5,6]. In response to these challenges, the development of new geosynthetic materials and optimized design technologies of reinforced slope has become an important research topic.

As a representative of emerging material technologies, negative Poisson's ratio (NPR) meta-materials have gradually become a research hotspot in geotechnical engineering due to their unique mechanical properties and structural design flexibility [7,8]. The most notable feature of NPR metamaterials is their lateral expansion when stretched. With the exceptional tensile performance and interface mechanism, they can address the limitations of traditional geomaterials in terms of tensile strength, shear resistance and energy absorption, etc. Although this material performs excellently in certain engineering applications, it still faces challenges, such as high costs, long production period, and unclear mechanisms underlying soil-structure interaction. Current researches mainly focus on using meta-anchors to reinforce the stability of rock slopes. However, the mechanical performance of other meta-geosynthetics, e.g., meta-geogrid, at cold region are still not well understood.