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Rock Engineering Design in Frozen and Thawing Rock: Current Approaches and Future Directions

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Abstract

The purpose of this review is to present the state-of-the-art methods, problems and potential future design techniques used for rock engineering in frozen ground, with particular regard to the design of mine openings in rock masses that may be subject to thawing. The impetus for this work is the recognition that civil and mining infrastructure is extending into such frozen material, and the design procedures currently available may not be optimal. Additionally, civilian infrastructure in frozen ground in alpine regions (e.g. central Europe) is also becoming subject to thawing conditions. In any such scenario, increased heat exchange with an exposed rock mass surface will cause thawing to occur. In general, a rock mass is stronger in frozen conditions than in dry conditions (i.e. without ice or water), but a rock mass will be least strong at the time ice-filled discontinuities are thawing, resulting in a significant shear strength reduction. In this review, we will discuss the various existing design methods in the context of the phenomena involved in the formation of frozen rock and the behaviour of thawing rock. We will show the deficiencies of these methods and highlight potential developments that will lead to future robust design protocols.

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Keywords: rock engineering design; thawing rock behaviour; frozen ground; permafrost

1. Introduction

Although research on permafrost began in the first half of the eighteenth century, the study of permafrost as an applied science (known as geocryology) began in the late nineteenth century when industrial development was accelerating in northern Russia. Applied research in permafrost was required to develop railways, mining

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operations, as well as to protect civil structures from freeze-thaw damage [1]. One of the earliest documented cases of permafrost engineering was in 1876 on the use of artificial freezing, which was applied at Brunkeberg tunnel in Stockholm [2].

Since the beginning of the twentieth century, the study of permafrost was further accelerated by the energy industry as well as different military research institutions, most originating in Russia [1–5]. The second World War gave impetus to some of the first formal geotechnical investigations for mining and civil structures in frozen ground [2]. Furthermore, during the Cold War, permafrost research was of great interest for American and Russian military researchers, so much so that a permafrost tunnel was excavated and operated by the U.S. Army Cold Regions Research and Engineering Laboratory (CCREL) in Alaska. The CCREL were tasked with investigating mining techniques and how to maintain underground excavations in perennially frozen ground [5].

In order to undertake engineering design in permafrost a characterisation of frozen ground is required. The next section will discuss the early characterisation of permafrost in the context of an engineering material. Sections 3 and 4 will expand upon this characterisation and introduce the design procedures currently used by mining and civil engineers and highlight potential developments that will be necessary to lead to a more robust design protocol.

2. Characterisation of permafrost

The characterisation of permanently frozen ground or permafrost began in the 1940s with a definition proposed by Muller [6], who stated that permafrost is a "thickness of soil or other superficial deposit, or even bedrock, at a variable depth beneath the surface of the earth in which a temperature below freezing has existed continually for a long time (from two to tens of thousands of years). [Permafrost] is defined exclusively on the basis of temperature, irrespective of texture." Since temperature defines whether the ground is considered as permafrost, it is possible for permafrost with different vertical distributions to exist. Figure 1 illustrates the different (i.e. continuous and discontinuous) permafrost textures and summarises Muller's definition. For the scope of this paper, a continuous permafrost zone is selected as the domain for which challenges faced in engineering design have been identified. However, the problems and proposed methodologies are not limited to continuous permafrost environments, but may also be relevant to discontinuous permafrost conditions. Notwithstanding, in either condition, permafrost characterisation is required to design infrastructure such as tunnels or slopes which consider the material behaviour.

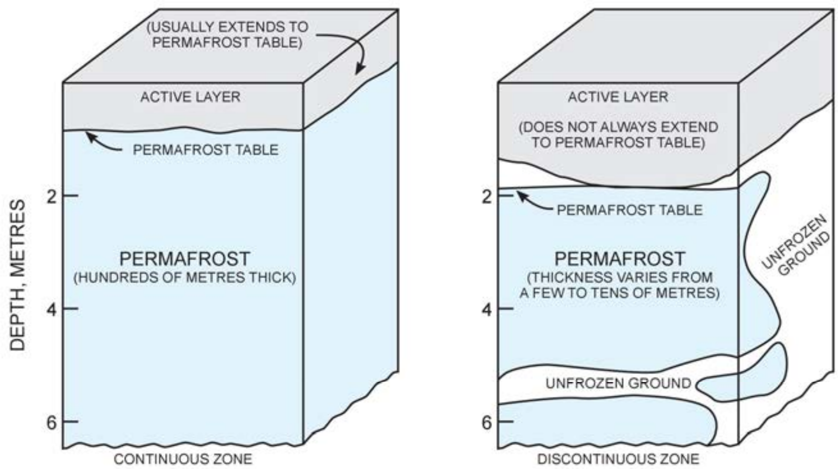

Fig. 1. Typical vertical distribution and thickness of permafrost (after [7]).

The characterisation of permafrost and efforts to understand the engineering behaviour of the material was accelerated by the technological revolution, and led by Russia during the construction of the Trans-Siberian Railroad