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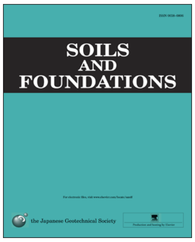

Effect of freeze–thaw cycles on the hydraulic conductivity of a compacted clayey silt and influence of the compaction energy

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Abstract

Compacted clay layers are often used in impervious barrier systems to prevent the migration of water and pollutants. Environmental factors, acting during or after the clay deposition, may affect the layer integrity and induce a variation of hydraulic conductivity over time. The aim of the present research is to assess this variation when induced by freeze–thaw cycles. The paper summarizes some results of tests performed on a series of clayey silt samples, reconstituted at various levels of compaction energy and subjected to cyclic freezing according to a controlled and repeatable procedure, set to reproduce the natural environmental conditions. The hydraulic conductivity is evaluated directly from a flexible wall permeameter and indirectly from oedometric tests. The results show the consequences of cyclic freezing in relation to the compaction level and lead to insights into the development of fracture networks responsible for the increase in hydraulic conductivity.

Keywords: Impervious barriers; Compaction energy; Hydraulic conductivity; Laboratory tests; Freezing

1. Introduction

In civil and environmental engineering, the impervious barriers for the prevention of water and pollutant migration are usually designed as layered systems, each layer serving a specific function, such as resistance to mechanical actions, drainage of collected fluids, and barrier to fluid percolation. The latter function is often provided by compacted clay layers, owing to the low hydraulic conductivity the clay can reach when properly compacted. The standard regulations for environmental protection in waste containment systems usually require a maximum value for the hydraulic conductivity of the upper cover, to limit the water infiltration into the waste body, and of the lower liner, to protect against leakage from the waste body to the foundation soil.

As examples, the European Community recommends a lower barrier with a maximum hydraulic conductivity of 10^{-9} m/s, or 10^{-7} m/s only in the case of inert waste, and an upper barrier that includes an "impermeable mineral layer" whenever the prevention of leachate formation is necessary (Annex 1 in Directive 1999/31/EC). Then, each member state is asked to implement these requirements into a local legislation (e.g., the Italian D. Lgs. N.36/2003). The US Environmental Protection Agency establishes that, in the case of a composite liner with a leachate collection system used at the bottom of a municipal solid waste landfill, the liner must include a layer of compacted soil with a hydraulic conductivity of no more than 10^{-9} m/s (CFR 40, I, 258-D), and that the landfill must be closed with a final system having a lower or equal hydraulic conductivity (CFR 40, I, 258-F).

These requirements must be guaranteed for the long term, to ensure a lifelong proper and environmentally safe performance of the containment system (Rowe, 2005).

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During the layer deposition and over the long term, factors of various origin may induce damage to the materials or to the layered structure, and hence, an increase in hydraulic conductivity (Chapuis, 2002). These factors basically have a mechanical origin, for instance, in the waste body settlement or in the sliding along inclined sides (Dixon et al., 2004; Jessberger and Stone, 1991; Jones and Dixon, 2005), or originate from the interaction with the atmosphere or from a chemical interaction with leachate (Benson, 2000). The soil–atmosphere interaction yields frost, desiccation, and internal or surface erosion of exposed and shallow layers. These actions usually have a cyclic occurrence, being the result of natural atmospheric events.

The physical process of freezing affects the soil micro-structure (Hohmann-Porebska, 2002), and the effects of freeze–thaw cycles on the hydraulic conductivity of compacted clays have been experimentally investigated by several authors (e.g., Benson et al., 1995; Chamberlain and Gow, 1979; Konrad, 1989), who also highlighted the importance of relating the sensitivity to freezing cycles to other factors, such as the physical properties of the clay (micro-structure, plasticity index, water retention, and swelling potential, etc) and the initial compaction conditions.

With reference to the initial conditions, Chamberlain et al. (1990) tested and compared slurry consolidated with compacted samples, to find that freeze–thaw cycles always induce an increase in hydraulic conductivity in consolidated samples, in particular a higher increase when the water content is higher, due to the development of large aggregates and paths of reduced flow resistance. On the contrary, the effect on compacted samples is not always consistent, depending on the water content, the degree of saturation, and the initial compaction.

Konrad (2010) emphasised the role of the changes in void ratio and proposed a framework for saturated consolidated samples to predict the freeze–thaw effects in a void ratio–stress–hydraulic conductivity space, which however could not be readily extended to compacted samples. For these, an experimental procedure was proposed to predict the changes in hydraulic conductivity.

Related to the compaction conditions are the findings by Kim and Daniel (1992), who observed that samples compacted wet of optimum are more susceptible to an increase in hydraulic conductivity than those compacted dry of optimum, although the former shrink while the latter expand. The decrease in void ratio associated with a large increase in hydraulic conductivity, in samples compacted wet of optimum, would confirm that freeze–thaw cycles expand the network of fluid-conducting pores. Moreover, Kim and Daniel (1992) found that an increase in compaction energy, though a variable less significant than the water content, has no consistent effect on the susceptibility to damage, increasing it in samples compacted wet of optimum, but slightly reducing it in samples compacted dry of optimum.

In addition to laboratory small-scale tests, large-scale and on-site investigations were also carried out to verify the effects of long-term freezing (Benson and Othman, 1993; Miller and Lee, 1999).

It is known that a cyclic freezing–thawing process also affects the soil mechanical properties, for instance, in terms of the shear strength response, oedometric compressibility, and particle crushability (e.g, Graham and Au, 1985; Ishikawa and Miura, 2011; Leroueil et al., 1991). Some of these aspects are still under investigation and certain issues are still open for examination, as summarized by Qi et al. (2006).

The comprehensive modelling of the freezing process requires a multi-physics approach and numerical solving procedures, due to the complex coupling of thermo-hydro-mechanical fields in multi-phase porous materials in the presence of liquid-to-solid phase changes (Coussy, 2005; Liu and Yu, 2011; Thomas et al., 2009). All additional insights, from experimental assessments into the factors that influence the soil response to cyclic freezing–thawing actions, may help the refinement of theoretical and numerical approaches and enhance the information database for engineering purposes.

In this framework, some results from a laboratory experimental programme are summarized herein, for the purpose of highlighting the effects of freeze–thaw cycles on the hydraulic conductivity of compacted clayey silt samples and, in particular, the role of the energy level applied in the compaction phase. The compaction energy is considered as a particularly relevant factor of influence, on density and hydraulic conductivity, and it represents a design parameter that could be prescribed in practise rules and controlled at the construction site, in order to achieve the best long-term performance of the barrier. In the investigation, all issues related to the influence on the soil mechanical properties were disregarded; they will be addressed in further experimental programmes.

The hydraulic conductivities were evaluated by oedometric and flexible wall permeameter tests, following the guidelines of ASTM D 6035 (2002). A comparison between the results also allows for recognizing the effect of freezing on the development of fracture networks at the small-scale.

2. Material and sample preparation

The soil used in the laboratory tests is classified as clayey silt, with inorganic medium plasticity clay, characterized by specific gravity $G_s = 2.74$, liquid limit $w_L = 32\%$, plasticity index $I_p = 14$, and the grain size distribution shown in Fig. 1 (Cervi, 2005). Three different compaction curves have been obtained by applying different values of compaction effort (Fig. 2): (A) the standard value, according to ASTM D 698 (2000) and corresponding to 593 kJ/m^3 (25 blows by the standard rammer), (B) a reduced value of 356 kJ/m^3 (15 blows), and (C) a reduced value of 237 kJ/m^3 (10 blows). This choice stems from the fact that the compaction procedure for clay barriers, such as landfill covers, may produce compaction efforts different from point to point, if not properly controlled, and that the standard effort reasonably represents a medium value. The areas of the clay barrier less accessible to heavy equipment or laid on inclined sides may be subjected to reduced compaction energy (Daniel and Benson, 1990).

The sample preparation and the testing conditions are the major factors affecting the experimental outcome. On the basis