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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

EXTERNAL REPORT
SCK•CEN-ER-255
14/Kbe/P-12

Effect of freeze-thaw cycles on hydraulic properties of (Boom) clay

Koen Beerten

SCK•CEN Contract: CO-90-08-2214-00
NIRAS/ONDRAF contract: CCHO 2009-0940000
Research Plan Geosynthesis

February, 2014

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Abstract

Cold climatic conditions as we have experienced in north-western Europe about 20.000 years ago are likely to return during the next 1 Ma. Permafrost (perennially frozen ground) might develop and although it is not very likely, the freezing front might reach the Boom Clay. In this report, a short overview is given on the possible consequences of freeze-thaw cycles on the hydraulic conductivity of clay sediments in general. In-situ and laboratory freeze-thaw tests indicate that after a few cycles, the hydraulic conductivity of the investigated clay samples (without overburden pressure) had increased by 2-3 orders of magnitude. Experiments with overburden pressure strongly suggest that the effect of freezing and thawing on the hydraulic conductivity of clay specimens is negligible as long as the burial depth is sufficient, i.e., at least several meters. Observations of hydraulic conductivity in a Boom Clay quarry are in line with the literature data, but freeze-thaw experiments on Boom Clay samples seem desirable in order to proof the transferability of the literature data to Boom Clay.

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1 Introduction

High-level and long-lived radioactive waste is a major radiological hazard to man and environment. ONDRAF/NIRAS, the Belgian agency for radioactive waste management, entitled to find a solution for this problem, currently investigates the safety and feasibility of geological disposal in poorly indurated plastic clays such as the Boom Clay and Ypresian clays. The Boom Clay is a thick and relatively homogeneous clay layer that is found in the outcrop and subcrop of a large part of north-eastern Belgium. Its thickness varies between several tens (outcrop) to more than 100 m (subcrop) while its top reaches depths of up to 200 m and more in the Campine area.

During the coldest parts of the Pleistocene glaciations, permafrost conditions were installed in north-western Europe with mean annual air temperatures often not exceeding -8°C for several millennia (Huijzer and Vandenberghe, 1998; Renssen and Vandenberghe, 2003; Busschers et al., 2007; summarized in Beerten, 2010). Such conditions promoted the penetration of the freezing front to greater depths, such that permafrost may have reached the Boom Clay. Numerical modelling suggests that permafrost in north-western Europe during the last glacial maximum (around 20 ka) could have been 200 m deep, thus reaching the top of the Boom Clay (Govaerts et al., 2011; De Craen et al., 2012). Furthermore, the thickness of the overburden may decrease in the course of the next millions of years (Beerten and Leterme, 2012), such that permafrost may more easily reach the Boom Clay layer. The question to be answered is how permafrost may affect the hydraulic properties of the Boom Clay.

The purpose of this report is to give a short overview on the current knowledge on the influence of (repeated) freeze-thaw cycles on hydraulic properties of (Boom) clay, as repeated freezing and thawing of the sediment would occur if permafrost reached the clay layer.

Initially, the goal of this report was to screen reports covering aspects of frozen Boom Clay during excavation of the HADES galleries and shaft sinking (Bastiaens and Bernier, 2006). However, an extensive search in the EURIDICE archives did not reveal substantial information on the topic. At that time, frozen clay samples were mostly used to measure geotechnical properties (e.g., Ouvry, 1986). Therefore, to assess the changes in hydraulic properties induced by freeze-thaw cycli, a review of open literature on frozen clay properties was done. It appears that these studies all deal with candidate barrier materials, e.g., liners for landfills, ponds and waste lagoons, and caps for remediation of contaminated sites.

2 Processes occurring during freezing

A saturated clay specimen subjected to freezing features a volume expansion (9% volume increase for the phase change from water to ice), which in turn causes a rearrangement of the solid matrix resulting in the creation of large voids filled with ice. Two types of voids may be created, which are oriented either vertically or horizontally. The first type is the result of desiccation (to be compared with freeze-drying), while the second type is the result of ice lens formation (Othman and Benson, 1993).

As the surface temperature of a soil sample drops below the freezing point, the freezing front penetrates the sample progressively (Figure 1a; x-axis = temperature; Thomas et al., 2009). The temperature at which pore water starts to freeze is the freezing temperature T_0 that corresponds with the freezing front. Phase change of pore water (into ice) occurs in the so-called frozen fringe, when the soil temperature falls below the freezing point T_0. Volumetric expansion of water due to the phase change (liquid to ice) causes an increase of pore pressure within the unfrozen pores of the frozen fringe (Figure 1b; x-axis = pressure). At the ice-water interface, a cryogenic suction gradient (Figure 1c; x-axis = suction, described by the so-called Clapeyron equation[1]), which is developed in response to the temperature gradient, causes the pore water in the unfrozen soil to migrate towards the freezing front (Figure 1d; x-axis = flow velocity), which in turn raises the pore pressure there. Ice segregation takes place if the pore pressure reaches a threshold value, and a new ice lens forms in the direction of heat removal (i.e., the direction of frost penetration). The accumulation of soil moisture and the volumetric expansion due to pore water phase change in both the fully frozen soils and ice lens finally result in frost heave (Figure 1e; x-axis = displacement). The vertical migration of water induces vertical shrinking cracks in the sample below the freezing front. These cracks will fill with ice if the freezing front moves (Othman and Benson, 1993).

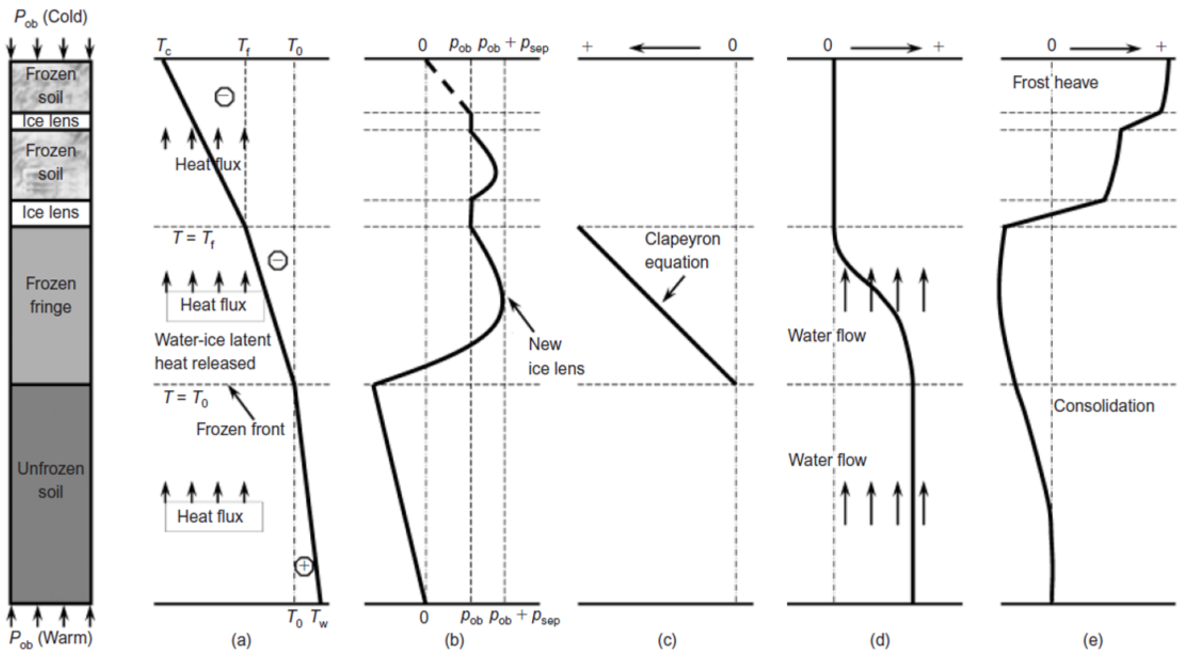

Figure 1 – Schematic representation of freezing soil with ice segregation (ice lens formation) (Fig. 2 from Thomas et al., 2009). (a): temperature; (b): pore pressure; (c): cryogenic suction; (d): water flow velocity; (e): displacement. T_0 = freezing temperature, T_f = temperature at the base of the ice lens, T_w = temperature at the warm end of the soil column, T_c = temperature at the cold end of the soil column, p_{ob} = surface overburden pressure, p_{sep} = separation strength.

3 Morphological changes during freeze-thaw

Samples that have been subjected to several freeze-thaw cycles (freezing rate of 2°C/min and no overburden pressure) show ice lenses in both vertical and horizontal cross-sections (Othman and Benson, 1993). Such samples also show a volume increase as a result of ice formation. As the number of cycles increases, the network of cracks becomes more extensive and more homogeneous. Typical dimensions quoted in Othman and Benson (1993) are 0.5-2 mm for ice lens thickness, and 3-7 mm for vertical spacing of ice lenses (laboratory experiments).

[1] The Clapeyron equation describes cryogenic suction. A detailed treatment of the equation is beyond the scope of this report.

4 Evolution of hydraulic conductivity during freeze-thaw cycles

4.1 Without significant overburden pressure

After the last freeze-thaw cycle, ice trapped in the sample melts and the cracks (horizontal and vertical) become conduits for percolating water. Obviously, this will have a strong impact on the hydraulic conductivity of clay samples. Several papers report on consistent increase of saturated hydraulic conductivity (K_{sat}) with 2-3 orders of magnitude after the sample had gone through several freeze-thaw cycles (e.g. Kraus and Benson, 1995). Parkview Clay (glacial till) for instance that was subjected to freeze-thaw cycles in the laboratory showed an increase from ~ 10^{-10} m/s before freezing and ~ 10^{-8} m/s after 5 freezing cycles (Figure 2). Similar clay samples that were subjected to freeze-thaw cycles in the field during an entire winter season (Wisconsin, USA) show dramatic K_{sat} changes from ~ 10^{-10} m/s to 10^{-6} m/s about 10-20 cm below the surface to no change at all below the maximum frost depth (> 70 cm depth). Similar results were obtained by Othman and Benson (1993) for Wisconsin Clay (lacustrine and residual weathering clays). It is interesting to note that laboratory experiments indicate no further K_{sat} changes after 3-4 freeze-thaw cycles.

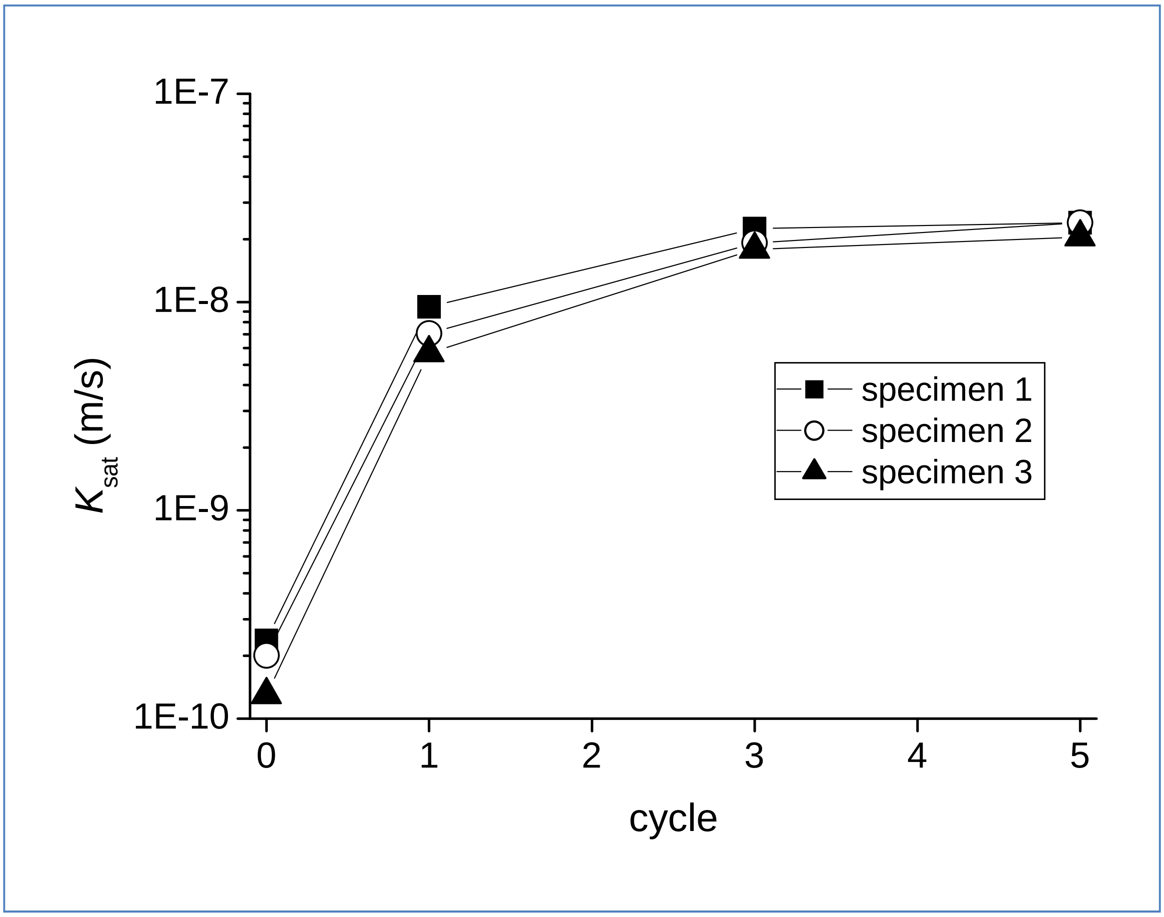

Figure 2 – Effect of the number of freeze-thaw cycles on hydraulic conductivity of clay specimens (data from Kraus and Benson, 1995).

4.2 With overburden pressure

Samples that have been subjected to 5 freeze-thaw cycles (no overburden pressure) have their K_{sat} values much higher than those without freeze-thaw (see previous section). However, as soon as overburden pressure is applied (25-150 kPa; 100 kPa equals ~ 5 m burial depth) after these freeze-thaw cycles, the hydraulic conductivity decreases again, approaching initial values (Othman and Benson, 1993). Even more important is the observation that the hydraulic conductivity ratio of samples undergoing freezing and thawing relative to the reference state is systematically lower if overburden pressure is applied *during* the freeze-thaw process, to the point that no difference is observed (ratio = 1) if the freezing treatment is applied with an overburden stress of 70 kPa for Wisconsin Clay samples (Othman and Benson, 1993; Figure 3). Similar results have been obtained from geosynthetic clay liners (initial K_{sat} ~ 10^{-9} m/s), where the effect on K_{sat} was negligible with stresses between 20 kPa and 60 kPa, even after not less than 150 freeze-thaw cycles (Podgorney and Bennett, 2006).

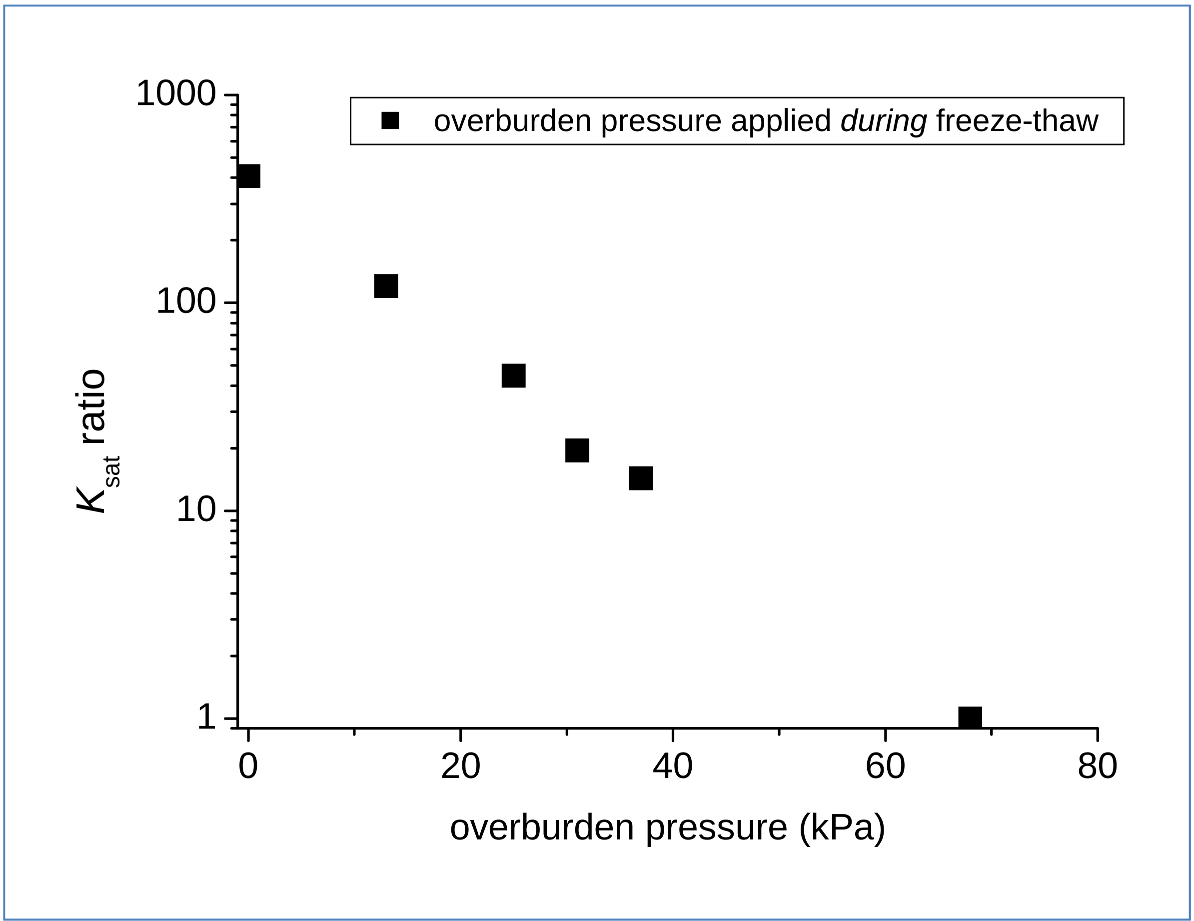

Figure 3 – Effect of applied overburden pressure during freeze-thaw cycles on K_{sat} ratio of disturbed (after freeze-thaw) versus undisturbed clay samples (initial K_{sat} ~ 10^{-10} m/s). Data from Othman and Benson (1993).

5 Observations from HADES

During construction of the first shaft, vertical freezing tubes were installed in order to be able to excavate the shaft in frozen sediment (sands from the Neogene aquifer and Boom Clay) without the risk of collapse. Amongst others, horizontal radial piezometers were installed at different depths after the shaft had been installed. The deepest set of piezometers was installed at 211 m depth (Aureole 4), in the top of the Boom Clay (Boeretang Member). Simultaneously, a temperature measurement equipment was installed to monitor the thermal evolution of the clay as a result of freezing (through freezing tubes). Piezometers are ca. 8 m long (extrados) with the first filter at 1.6 m and the second filter at 7.4 m.

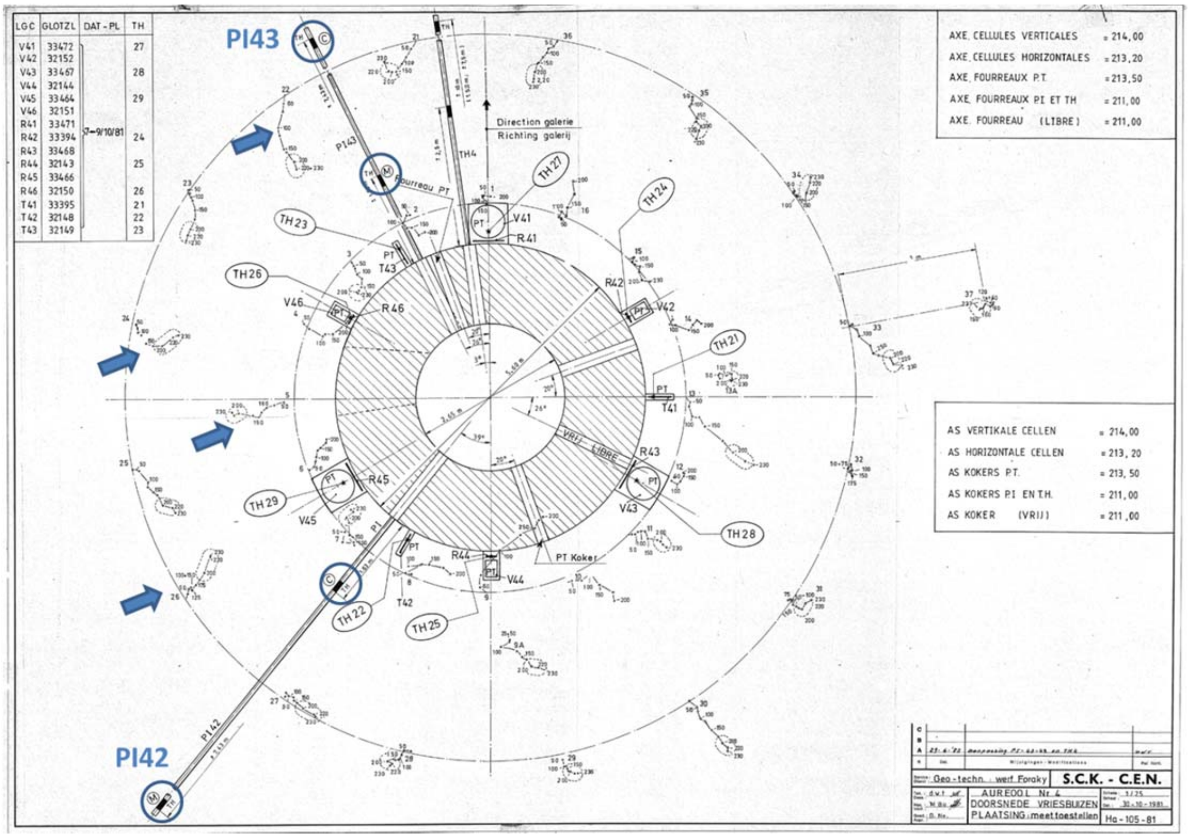

Figure 4 – Horizontal cross section through aureole 4, at ca. 211 m depth, showing the position of two radial piezometers PI42 and PI43, their corresponding filters (blue circles) and the horizontal projection of the vertical trajectory of the freezing tubes from which several are indicated by the blue arrow as an example. From the EURIDICE archive.

In Aureole 4, the interstitial pore water pressure was measured between 04/05/1982 and 10/11/1982. The filters which were in the fully frozen zone (between -4°C and -11°C) show high pore pressures of between 28-36 bar at the time of freezing, in comparison to filters in the non-frozen zone (between -1°C and 4°C) with pore pressures between 18-27 bar. Thus, given the average in situ pore pressure of 20-23 bar for Boom Clay (Bastiaens and Bernier, 2006; present condition, unfrozen), the filters in the frozen zone yield overpressures. Unfortunately, there are no pore pressure data after defrosting of the clay, such that the actual impact cannot really be estimated.

6 Hydraulic conductivity measurements in Boom Clay outcrops

In 2003, sampling by SCK was performed in quarry Swenden (Terhagen, Rumst) (Figure 5). Small steps were created to be able to sample fresh clay, for both vertical (K_v) and horizontal (K_h) hydraulic conductivity measurements. Hydraulic conductivity was measured using the standard SCK permeameter setup (see, e.g., Yu et al., 2011).

In the Putte member, 10 m below the surface, a small increase in K_v and a larger increase in K_h is observed. A large increase in K_h was also observed in the nearby Doel-2b data (2-3 orders of magnitude, up to 10^{-9} m/s)(Figure 6 for quarry Swenden and Figure 7 for Doel-2b). K values in the underlying Terhagen member, ca. 20 m below the surface, seem to be in line with those of Boom Clay in Doel-2b.

Given the absence of clear signs of chemical weathering, we hypothesize – in line with the theory of frozen soil physics as explained above – that physical processes such as permafrost development and ice lens formation might be responsible for the sharp increase in K values in the shallow burial realm of the Putte member in this quarry. The accumulation of pore water due to cryogenic suction, and the volumetric expansion of the phase change water to ice might induce horizontal cracks that after thawing become a preferential flow path. Evidently, this hypothesis needs to be verified. Note that the 2-3 orders of magnitude increase of K is in line with freeze-thaw laboratory experiments as explained above (section Evolution of hydraulic conductivity during freeze-thaw cycles).

Figure 5 – Sampling for hydraulic conductivity in the Putte Member (Terhagen, Rumst).

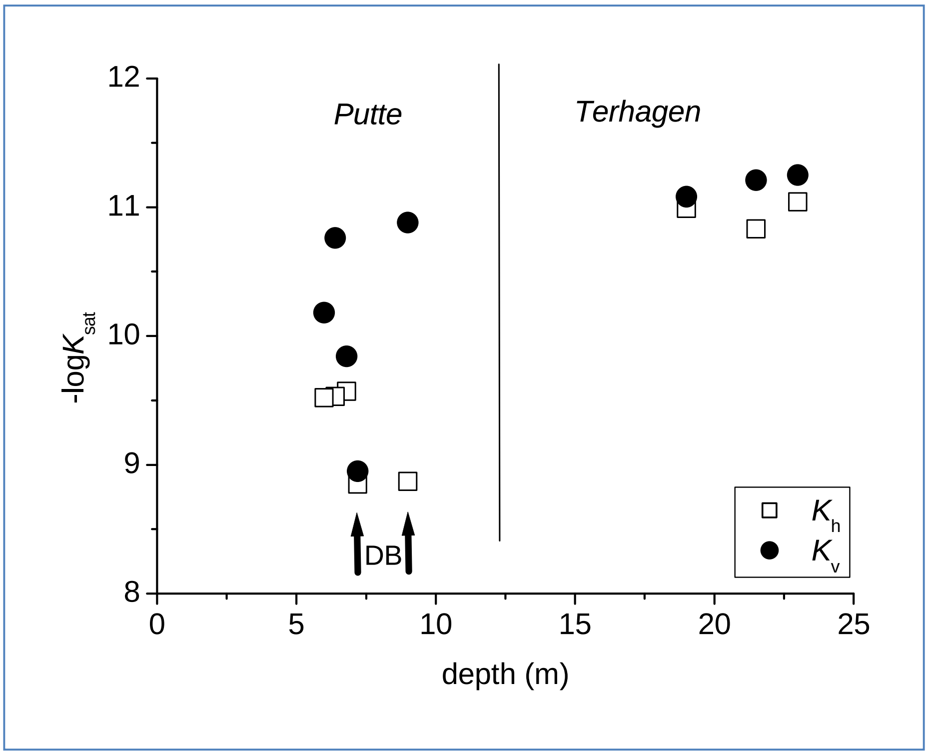

Figure 6 – Vertical (K_v) and horizontal (K_h) hydraulic conductivity in the Terhagen and Putte Members in quarry Swenden. Values are given as the negative logarithm of the hydraulic conductivity expressed in m/s. DB = double band.

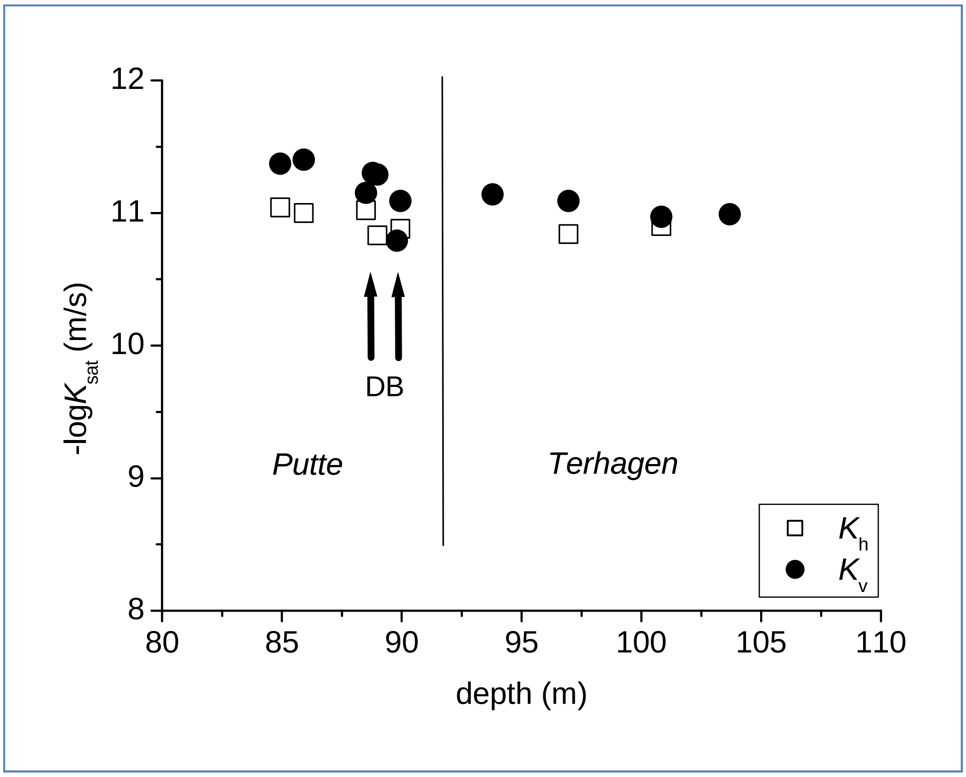

Figure 7 – Vertical (K_v) and horizontal (K_h) hydraulic conductivity in the Terhagen and Putte Members as sampled in the Doel-2 borehole. Values are given as the negative logarithm of the hydraulic conductivity expressed in m/s. DB = double band.

7 Discussion: permafrost in Boom Clay

During the coldest stages of a glacial cycle, and given the current depth, it cannot be ruled out that permafrost will reach the top of the Boom Clay in Mol, or will even penetrate it (Govaerts et al., 2011). However, as long as the Boom Clay remains at depths with overburden pressure of several 10 kPa (corresponding to several meters of overburden), it is highly unlikely that permafrost development will have an effect on the hydraulic conductivity of the clay. If permafrost would have reached Boom Clay in the past (Pleistocene glaciations), it is also unlikely that the present-day observed hydraulic conductivity at the Mol site is biased given the current burial depth (i.e., 223 m depth for the HADES underground research facility) that is equivalent to a total pressure of 4.5 MPa (Bastiaens and Bernier, 2005). It should be noted however that the experiments reviewed here had an initial hydraulic conductivity of 10^{-10} m/s. The effect on clay samples with lower initial K_{sat} values, such as the Boom Clay, has not been investigated.

8 Conclusion

Freeze-thaw cycles have a negligible effect on the hydraulic conductivity of clay samples with initial K_{sat} values around 10^{-10} m/s, as long as the overburden pressure is sufficiently large as to avoid cracking. The effect on clay samples with lower initial K_{sat} values, such as the Boom Clay, has not been investigated. We suggest that several freeze-thaw experiments should be conducted to confirm the transferability of the literature data to Boom Clay.

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