Hydraulic conductivity of Boom Clay in north-east Belgium

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ABSTRACT. *Hydraulic conductivities of Boom Clay measured through various testing techniques in the laboratory exhibit similar K values in the order of 10^{-12} m/s. In situ measurements obtained from various scales at the HADES underground research facility yield K values that are very similar to values measured in the laboratory on samples of a few centimetres. Spatial analysis of K values across the Boom Clay at the Mol site reveals a typical profile with a very homogenous 61-m thick central part (the Putte and Terhagen Members), which is also the least permeable part of the Boom Clay. The geometric mean of the vertical (K_v) and horizontal (K_h) hydraulic conductivities for the Putte and Terhagen Members at the Mol site are 1.7×10^{-12} and 4.4×10^{-12} m/s, respectively, with a vertical anisotropy Kh/Kv of about 2.5. Higher K values, but still low (10^{-12} to 10^{-10} m/s), are observed in the more silty zones above and below. A regional analysis of vertical K variability of the Boom Clay in the northeast of Belgium confirms this typical K profile of the Boom Clay based on test results from other four regional boreholes. Furthermore, an increase in overall Boom Clay vertical hydraulic conductivity from the east towards the west in north-east Belgium was observed.*

KEY WORDS: *North-east Belgium; geological disposal of radioactive waste; low permeable clay; measurement of hydraulic conductivity, grain-size.*

1. Introduction

Disposal in deep clay formations is one of the promising final solutions for the management of high-level and long-lived radioactive waste. In Belgium, the Boom Clay is studied as the reference host formation owing to its very low permeability, strong sorption capacity for many radionuclides, absence of preferential migration pathways, as well as its favourable creep and swelling properties. Furthermore, the low vertical hydraulic gradient is an additional favourable characteristic for the Boom Clay in the north-eastern part of Belgium (ONDRAF/NIRAS, 2001).

The assessment of the long-term barrier function of the host clay formation in the framework of radioactive waste disposal requires a rigorous quantitative characterization of the hydraulic conductivity (*K*) of Boom Clay. At the Belgian nuclear research centre (SCK·CEN), determinations of hydraulic conductivities of the Boom Clay have been carried out since more than 30 years in various national (ONDRAF/NIRAS, 1989 & 2001; Yu et al., 2011) and international research programmes (Beaufays et al., 1994; Volckaert et al., 1995; Bernier et al., 2006). A large quantity of *K* measurements has been performed through fluid flow and tracer experiments both *in situ* at the HADES underground research facility (URF) in Mol, Belgium, and in the above-surface laboratories on samples from undisturbed clay cores. Such cores have been obtained from several deep boreholes in northeast Belgium in an area of more than 1000 km^2.

The objective of this paper is therefore to present a synthesis of the hydraulic conductivities determined for the undisturbed Boom Clay in the past few decades. This study makes use of *K* values obtained not only in the local investigation area at the Mol site, but also from four other boreholes named Zoersel, Doel-2b, Weelde-1 and Essen-1 (Figure 1). In this way, the hydraulic conductivity can be investigated in the regional extent of the Boom Clay.

2. Techniques for hydraulic conductivity measurements

Throughout the years, the hydraulic conductivity (*K*) of Boom Clay has been determined in several ways and at several scales, from core scale (several centimetres) to piezometer scale (several decimetres), up to gallery scale (several meters or tens of meters). In the following, a brief description of various testing techniques adopted by SCK•CEN to determine hydraulic conductivity is presented. More detailed information can be found in Yu et al. (2011).

Laboratory experiments

The majority of hydraulic conductivity determinations on Boom Clay samples in the laboratory are based on two types of experiments. The first type is a percolation experiment used in the framework of radionuclide migration studies, aiming at determining physical transport parameters. The second type of experiment is a hydraulic conductivity test using permeameter/isostatic/triaxial cells which are designed specifically to determine the hydraulic conductivity of low-permeable media.

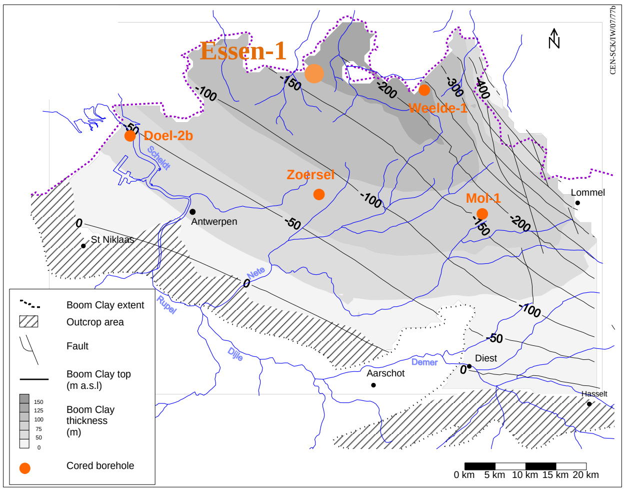

Figure 1: Geographic extent of the Boom Clay in NW Belgium with indication of depth and thickness (after Wemaere et al., 2008).

For the percolation experiment the clay sample is confined between two filters in a permeation cell and continuously percolated with Boom Clay interstitial water under a constant pressure gradient over the clay plug. The diameter of the clay plug is 3.8 cm. The length of the sample is 3.2 cm or 7.2 cm (sample volume ≈ 36 or 82 cm^3). The applied hydraulic pressure difference was mostly 1.23 to 1.35 MPa. Detailed description of the percolation experiments can be found in Aertsens et al. (2004). For the permeameter test undisturbed 5-cm long and 3.8-cm diameter clay samples (sample volume ≈ 57 cm^3) were cut and fitted into a rigid stainless cylindrical cell with two sintered stainless steel filters at both ends. De-ionised water is injected at the bottom of the sample under a constant upward pressure of about 0.63 MPa. (Wemaere et al., 2008).

Isostatic/triaxial apparatus allows re-saturating and reconsolidating the clay sample to its *in situ* stress state prior to hydraulic conductivity testing by applying a stepwise compression. At SCK•CEN a custom-built isostatic cell controls the isostatic confining pressure and the effective stress with high precision for 30-cm long and 8-cm diameter cylindrical clay cores (Volckaert et al., 1995). The ~1500 cm^3 sample is left to consolidate and re-saturate under a confining stress of 4.4 MPa and a pore water pressure of 2.2 MPa, which is equivalent to the *in situ* interstitial pressure at the level of the HADES URF. The same principle with the triaxial cell was used by the British Geological Survey (BGS) on 4.9-cm diameter and 4.9-cm long Boom Clay samples for K_v and 2.45-cm long samples for K_h determination (Volckaert et al., 1995).

In situ experiments

In situ hydraulic tests on the Boom Clay were performed almost exclusively in the HADES URF, where the presence of the undisturbed clay allows for more complex borehole instrumentations. This paper only focuses on *K* determinations for undisturbed Boom Clay, therefore those filters located within the disturbed zone (i.e. excavation damaged zone) are excluded.

The principle of single-point piezometer test is to use a stainless steel piezometer with a pervious screen buried in the porous clay matrix to measure the quasi steady-state flow rate of the interstitial clay formation fluid from the piezometer at the hydraulic gradient created between the *in situ* pore water pressure and atmospheric pressure inside the piezometer (Beaufays et al., 1987). The measurement volume associated with the hydraulic conductivity estimated from the piezometer tests depends on the filter size and the *in situ* pore water pressure around the piezometer, and is up to roughly several thousand cm^3 which is at least two orders of magnitude larger than that of the migration and permeameter tests discussed in the previous section.

An interference test measures hydraulic conductivity of clay with a multi-piezometer which consists of multiple tubular screens (generally 6 to 15 cm in diameter) in stainless steel mounted on the piezometer body directly placed in the clay formation from within the gallery. The piezometer filters are connected to the sampling point in the URF by small diameter stainless steel tubes. The filter can be placed in vertical or horizontal direction which yields values of respectively horizontal and vertical hydraulic conductivity (De Cannière et al., 1992; Volckaert et al., 1995).

A single large-scale hydraulic experiment, often called macro-permeameter test, was performed in 1993 in a separate experimental shaft and gallery connected to the main gallery of the HADES URF. The small shaft and gallery have an external diameter of two metres, with a length of 21 m and 7 m, respectively. The basic principle of the experiment was to have the experimental shaft and gallery act as a large borehole filter (macro-permeameter with a flow cross-sectional area of about 190 m^2) and a corresponding measurement volume of at least several hundred m^3. The water flow through the void spaces of the macro permeameter was observed for a total of 1050 consecutive days (Ortiz et al., 1996).

3. Hydraulic conductivity data at the Mol site

A large fraction of the hydraulic conductivity data of the Boom Clay at the Mol site is associated with the Mol-1 borehole, which was drilled at about 50 m from the second shaft of the HADES URF. The Mol-1 borehole was drilled in 1997, down to a depth of 567.65 m below the ground surface. It was cored from 145.37 to 326.98 m, completely covering the Boom Formation. Investigation at the Mol-1 borehole provides a detailed hydraulic conductivity profile of the entire Boom Clay, at a vertical spatial resolution of 1~2 m. According to the orientation of the clay core (parallel or transversal to the stratigraphic plane), respectively K_h and K_v were measured by means of permeameter and percolation tests (Wemaere et al., 2002 & 2008). The Boom Formation can be subdivided into four main stratigraphic units (Belgian Subcommission of Tertiary Stratigraphy, 2011).The main stratigraphic sub-units for the Mol-1 borehole together with their respective K_h and K_v values are listed in Table 1.

Table 1: Stratigraphic division of the Boom Clay together with K_h and K_v for each sub unit measured by means of permeameter tests and percolation tests at the Mol-1 borehole (after Wemaere et al., 2008).

Sub unit	Stratigraphic subdivisions (m below ground surface)			Vertical hydraulic conductivity			Horizontal hydraulic conductivity		
	Top	Bottom	thickness	n[§]	K_v (m/s)[‡]	s[†]	n	K_H (m/s)	s
Boeretang	-186.1	-211.2	~25.1	16	2.8×10^{-12}	0.2	3	5.0×10^{-12}	0.1
Putte	-211.2	-257.2	~46.0	29	2.4×10^{-12}	0.2	10	4.8×10^{-12}	0.1
Terhagen	-257.2	-272.8	~15.6	9	2.0×10^{-12}	0.1	2	6.2×10^{-12}	0.2
Belsele-Waas	-272.8	-288.7	~15.9	10	1.6×10^{-11}	1.0	5	5.7×10^{-11}	1.2
Boom Clay unit	-186.1	-288.7	~102.6	64	2.8×10^{-12}		20	1.3×10^{-11}	

§ n: sample of analyses;

† s is the standard derivation of log (K): $\sqrt{\frac{(x-\bar{x})^2}{n-1}}$

‡ K values for sub-unit are geometric means: $K_{geom} = \sqrt[n]{K_1 \cdot K_2 \cdots K_n}$, Boom Clay unit K values are harmonic mean (K_v) and arithmetic mean (K_H) of K_{geom} weighted by the thickness (H_i) of each sub unit, H is total Boom Clay thickness:

$$K_v = \frac{H}{\sum_{i=1}^{n}\left(\frac{H_i}{K_{vi}geom}\right)} \quad \text{and} \quad K_h = \frac{1}{H}\sum_{i=1}^{n} K_{hi}geom \cdot H_i$$

Additionally, the HADES URF, where *in situ* tests were performed and numerous Boom Clay samples were taken for laboratory K determination, provides supplementary information on K values for the central part of the Boom Formation. More than 50 determinations of hydraulic conductivity have been performed *in situ*, by single point piezometer tests or by interference multi-piezometer tests. Furthermore, there is one large scale *in situ* test– for dimensions see higher (Beaufays et al., 1987; De Cannière et al., 1992 & 1994; Volckaert et al., 1995; Ortiz et al., 1996 &1997; Bernier et al., 2004; Yu et al., 2011). Most *in situ* tests were carried out in the central Putte Member. Figure 2 provides a vertical profile of the K values for the entire section of the Boom Formation at the Mol site. Geometric mean vertical (K_v) and horizontal (K_h) hydraulic conductivities derived from laboratory tests and equivalent hydraulic conductivities (K) obtained from *in situ* tests are illustrated respectively by the dashed, dash-dotted and solid lines for each sub unit.

At a first glance the vertical variations in *K* for the whole Boom Clay section indicate that the highest K_v values are clearly situated in the Belsele-Waas Member, the Boeretang Member and the "double band" (db) (Figure 2). Except for the laboratory *K* measurements from the Mol-1 borehole providing *K* information for all four sub-units, all *in situ* test locations are within the Putte and Terhagen Members (except the piezometer test R13U which lies in the upper Boeretang Member). Therefore, the following investigation about differences in variability in *K* according to the sub units is only based on hydraulic conductivities measured by means of permeameter and percolation tests on samples from the Mol-1 borehole. Table 1 summarizes the K_h and K_v values for each sub-unit measured at the Mol-1 borehole. The overall highest mean *K* values and highest heterogeneity are measured for the Belsele-Waas Member, which are attributed to its high sand content of 22% on average. The Putte and Terhagen Members, which represent the central part of the Boom Formation, show the lowest overall mean values of hydraulic conductivity and display the lowest heterogeneity with depth, except for the sandy "double band" (db) in the lower Putte Member. The very silty bed of the Boeretang Member (average silt content of 70%) yields similar or slightly higher *K* values than the Putte and Terhagen Members, but with some more variations according to depth.

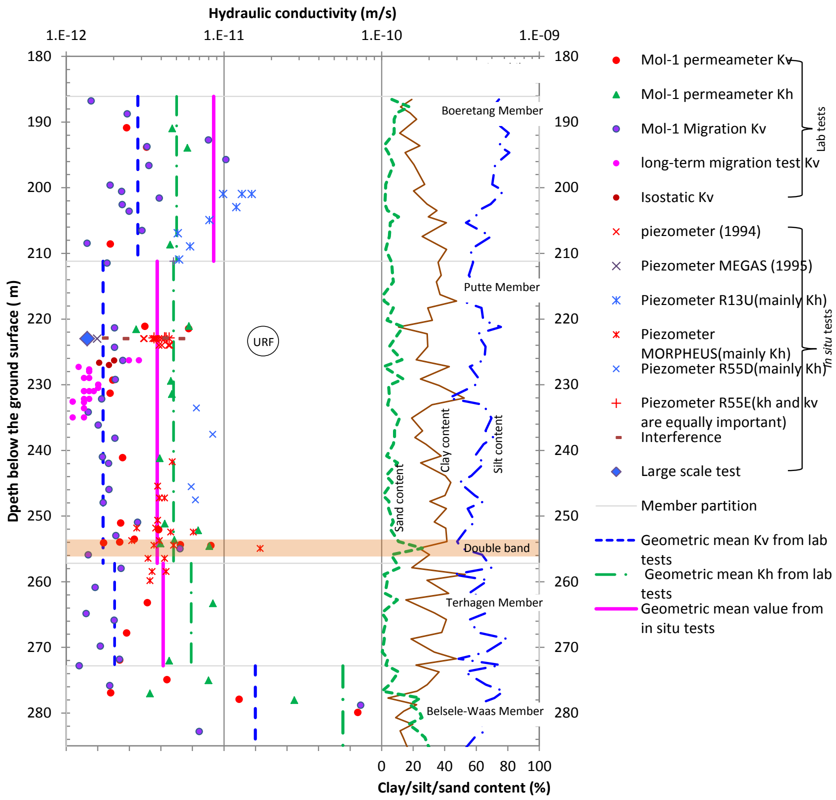

Figure 2: Hydraulic conductivity profile of Boom Clay at the Mol site based on lab tests and *in situ* tests at the HADES URF (clay: <2 µm, silt: ≥2 µm and <62.5 µm, sand: ≥62.5 µm).

The summary of hydraulic conductivities measured from various techniques for the Putte and Terhagen Members in Figure 3 reveals a very consistent estimate of the hydraulic conductivity considering the 95% confidence intervals. *In situ* measurements made on a few decimeters long filters and on the large-scale *in situ* test at the HADES URF yield equivalent K values (geometric mean K=3.5×10^{-12} m/s for piezometer tests and 1.4×10^{-12} m/s for large-scale *in situ* test) that are very similar to values measured in the laboratory on centimeter scale samples (geometric mean K_v = 1.9×10^{-12} and K_h = 4.3×10^{-12} m/s). Consequently, parameter values measured on a centimetre scale can be applied to a scale of tens of metres, in so far as the considered clay volume can be considered to be homogeneous for that parameter (Marivoet et al., 2009).

Based on all the laboratory (29 K_h and 119 K_v) and interference tests (2 K_h and 2 K_v) carried out at the Mol site for which directional values could be unequivocally defined, the geometric means of the vertical and horizontal hydraulic conductivities for the Putte and Terhagen Members are respectively 1.7×10^{-12} and 4.4×10^{-12} m/s with an anisotropy ratio K_h/K_v of about 2.5.

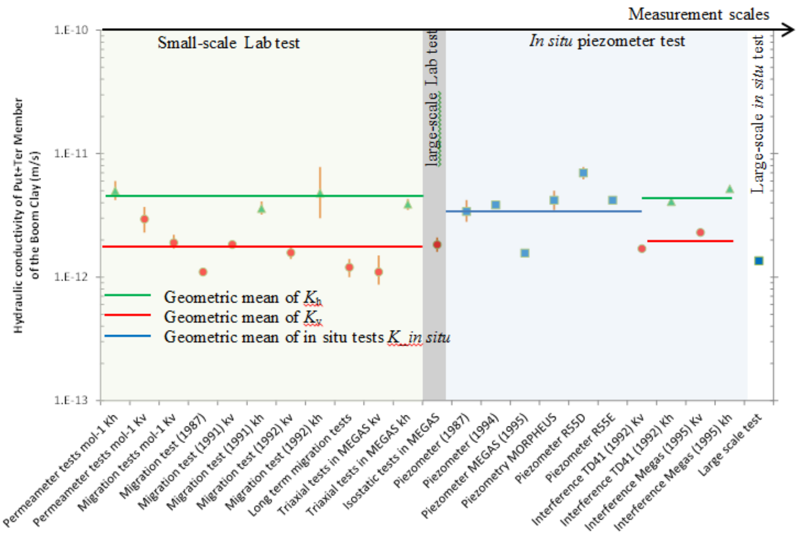

Figure 3: Overview of hydraulic conductivity values (m/s) for Putte and Terhagen Members at the Mol site. Vertical bars represent the 95% confidence interval.

4. Regional variability in the hydraulic conductivity of the Boom Clay

An intensive characterisation programme on small core plugs was undertaken at four additional locations, i.e. the Zoersel, Doel-2b, Weelde-1 and Essen-1 boreholes (Figure 1). These boreholes were drilled in the regional investigation area which covers about 1100 km^2 of the occurrence area of the Boom Clay in northeast

Belgium. Note that at the Doel-2b location the top of the Boom Clay is at a depth of 50 m while at Weelde-1 it is at roughly 250 m below surface, owing to the northeast oriented downward slope of 1-2%. At these two locations, the thickness of Boom Clay is respectively ~25 and ~125 m. In all five boreholes, contiguous coring was performed followed by core sample collection for hydraulic conductivity determination using the same permeameter and percolation experiments as discussed above.

Detailed descriptions and analyses of the borehole cores, interpretation of the geophysical logging performed in the open-hole and hydraulic conductivity measurements are available in Wemaere et al. (2002, 2004, 2005, 2008) and Labat et al. (2008). Spatial variability in hydraulic conductivity according to the stratigraphic sub-units is displayed in Figure 4.

A typical *K* profile of the Boom Clay observed in all boreholes exhibits a less permeable and relatively more homogeneous central Putte and Terhagen Member, and a more permeable and heterogeneous overlying Boeretang Member and underlying Belsele-Waas Member. Generally, the vertical hydraulic conductivities of the Putte and Terhagen Members are on the order of 10^{-12} m/s. A general increasing trend in overall Boom Clay vertical hydraulic conductivity is observed from east towards west, *i.e.* increasing from Mol (2.8×10^{-12} m/s) → Weelde (4.0×10^{-12} m/s) → Zoersel (5.5×10^{-12} m/s) → Doel (8.0×10^{-12} m/s) → Essen (8.5×10^{-12} m/s). A similar trend is observed for K_h with Essen-1 having the highest overall K_h (4.7×10^{-10} m/s).

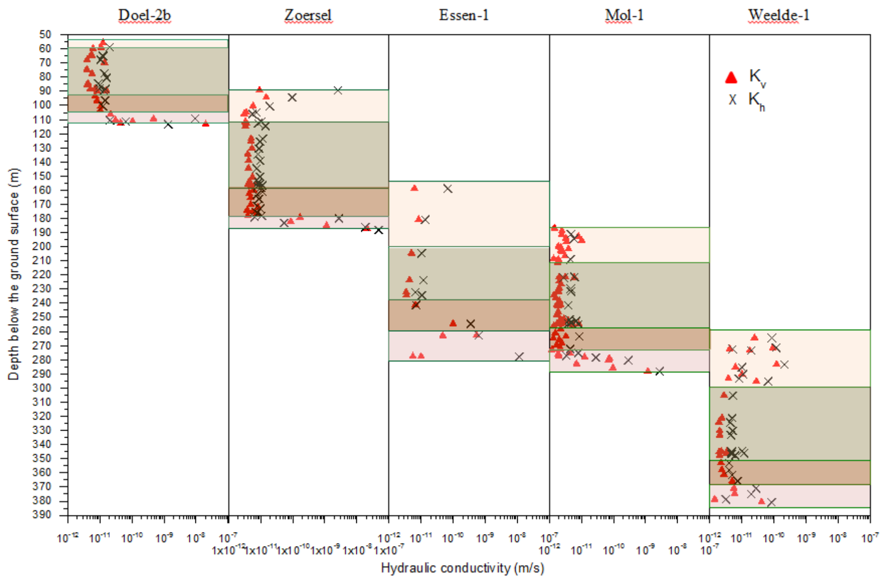

Figure 4: Spatial variability of hydraulic conductivity in five boreholes. Sub-units for all boreholes are identical (from top to bottom): Boeretang Member, Putte Member, Terhagen member, Belsele-Waas Member.

5. Conclusions

The hydraulic conductivity of the Boom Clay has been the subject of intensive research for about thirty years. *K* values at the Mol site are derived from hydraulic laboratory tests conducted on small (cm scale) clay samples collected from the HADES URF and from the Mol-1 borehole or from larger-scale (dm to m scale) *in situ* piezometer tests in the HADES URF mainly for the Putte and Terhagen Members. The Terhagen Member and the Putte Member can be treated as one single ~60-m thick hydraulic unit at the Mol site due to their similarity in hydraulic and transport properties. They form the most homogeneous and the least permeable part of the Boom Formation, except for 1-2 thin layers with relatively higher permeability known as "double band" in the lower part of the Putte Member. Nearly all the *K* values measured for the Putte and Terhagen Members at the Mol site are in the approximate range $1.5 – 8\times10^{-12}$ m/s.

The regional variability in hydraulic conductivity of the Boom Formation was examined at four additional boreholes covering an area of about 1100 km^2. A typical vertical *K* profile of the Boom Clay was observed in all five boreholes. An increase in overall Boom Clay vertical hydraulic conductivity is observed from east towards the west.

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