Experimental device and testing procedures to determine the hydraulic conductivity anisotropy of compacted tills

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ABSTRACT
Compacted tills are widely use as cores of embankment dams in northern Quebec. It is expected that placement method in successive layers may result in a permeability anisotropy (r_K) different from unity. A new cubic permeameter was designed to obtain the permeability ratio on the same sample. A special testing procedure was developed to limit seepage trough the inactive porous stones, i.e. the porous stones parallel to the seepage flow. Bovine gelatin, solid at temperatures less than 30 ℃ was used and proved to be highly efficient in sealing the inactive porous elements. Heating at 60 ℃ allows to remove the liquid gelatin without the need of dismantling the cell. A new percolation test can then be conducted on the same sample but in a different direction. Preliminary tests on a compacted glacial till have shown that the hydraulic conductivity values compared well to those obtained from tests using a flexible wall permeameter. The k anisotropy was found close to unity, which was also reported by other studies on similar soils.
Key words: permeability, anisotropy, cubical permeability cell, compacted tills, embankment dam.

RÉSUMÉ
Les tills compactés sont largement utilisés comme noyau des barrages en remblai dans le nord-québécois. La mise en place en différentes couches successives laisse présager un ratio d'anisotropie (r_K) de la perméabilité différent de l'unité. Une nouveau perméamètre cubique a été conçu afin d'obtenir une valeur de r_K sur un même échantillon. Une procédure spéciale a été développée afin de limiter l'écoulement dans les pierres poreuses inactives, i.e. parallèles à l'écoulement. Une solution de gélatine bovine qui est solide à une température inférieure à 30℃ est utilisée afin de sceller ces pierres inactives. De l'eau chaude à 60℃ permet de chasser cette gélatine sans démanteler la cellule. Un nouvel essai de perméabilité peut ainsi être effectué sur le même échantillon, mais selon une autre direction. Des essais préliminaires sur des tills québécois ont permis de démontrer que les valeurs de conductivité hydraulique correspondent aux valeurs obtenues par un perméamètre flexible. Une valeur de r_K près de l'unité a été trouvée, ces valeurs ont aussi été répertoriées dans d'autres études sur des sols similaires.
Mots clés: perméabilité, anisotropie, perméamètre cubique, tills compactés, barrage en remblai

1 INTRODUCTION

Compacted glacial tills are widely used as impervious cores of embankment dams in northern Quebec. Tills are characterized by a large range of particle sizes. The fine matrix provides low permeability characteristics to the materials while the granular skeleton provides small compressibility and increased shear resistance (Rahardjo and al. 2008 and Shafiee 2008).

It is expected that placement methods in successive layers may result in hydraulic conductivity ratios ($r_K = k_h/k_v$) different from unity. Variability between the materials used for each layer in a dam project induces a difference between the horizontal and vertical hydraulic conductivity values. In other words, material heterogeneity may affect the hydraulic conductivity anisotropy. Chan and Kenney (1973) evaluated the r_K values on a varved clay. Other researchers (Chapuis et al. 1989; Leroueil et al. 1990 2002; Shafiee 2008) evaluated the hydraulic conductivity anisotropy on homogeneous samples. These r_K values are commonly referred to as the inherent permeability anisotropy. According to Scholes et al. (2007) the inherent anisotropy could be partly explained by the tortuosity of the flow paths due to the shape and orientation of the particles (Figure 1).

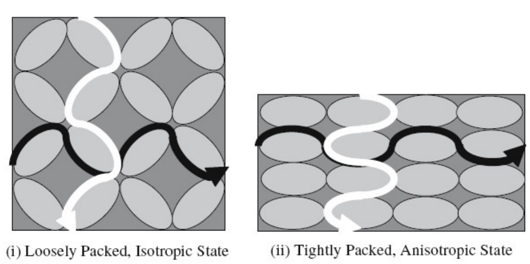

Figure 1. Tortuosity of the flow path (from Scholes et al. 2007)

However, the flow through a porous medium does not occur in a plan, but in a three-dimensional space. This obviously brings into question the real influence of coarse particles on seepage flows. This is especially the case for tills where the proportion of coarse particles is relatively low.

To improve our knowledge on seepage through zoned earth dams, the hydraulic conductivity ratio will be investigated in the laboratory on homogeneous samples using a new testing device. This paper mainly presents the new experimental testing device and outlines the testing procedures to determine the hydraulic conductivity anisotropy on compacted tills.

2 REVIEW OF THE EXPERIMENTAL DEVICES

In recent decades, different methods were used to evaluate the hydraulic conductivity anisotropy. Chapuis and Gill (1989) provided an overview of methods used to assess the hydraulic conductivity anisotropy for rocks and clays materials. These authors also outlined the weaknesses of these different methods:

- Porous plates smaller than the sample affect the flow path and require a correction factor;
- A permeameter with lateral leakage along the rigid walls must be calibrated;
- Difficulty to apply high confining pressures to ensure fully saturated conditions in compacted samples.

Leroueil et al. (1990) used a radial flow cell to quantify the horizontal hydraulic conductivity and a flexible wall permeameter to assess the vertical hydraulic conductivity of clays which were fully saturated . Despite the fact that they have quantified r_K on two separate samples, they obtained a value near 1 for homogenous clays. With a similar device, Leroueil et al. (2002) examined the anisotropy of compacted and fully saturated glacial tills. Their results provide hydraulic conductivity ratios close to 1.0 and always less than 1.4.

In a recent study, Shafiee (2008) carried out tests in a cubical permeability cell with removable to evaluate the hydraulic conductivity in both vertical and horizontal directions on the same sample. In Shafiee's device a disturbed surface can occur while removing the plates, thus causing preferential flow along these disturbed interfaces. Moreover, the water head at both ends does not seem to be applied to the entire surface of the sample thus requiring the use of correction factor as shown by Chapuis and Gill (1989).

The value of the hydraulic conductivity anisotropy is affected to some extent by the experimental device. A new cell limiting or even excluding all problems listed in the experimental set ups, was thus designed at Université Laval.

2.1 Components of the cubic cell

A cubical cell composed of four porous plates has been built to allow vertical and horizontal seepage through the same sample. Top (TPP-V2) and bottom (BPP-V1) porous plates allowing vertical seepage testing as well as two side porous plates (LPP-H1 and RPP-H2) for horizontal seepage are indicated on Figure 2 showing a cross section of the cubical permeameter. The photographs shown in Figure 3 illustrate the various components of the permeameter

A Mariotte burette applies a constant water head on the BPP-V1 for the vertical seepage. The same burette is used on the LPP-H1 for the horizontal seepage test. A graduated cylinder overflow applies a constant water head to the exit of the system, more specifically on the TPP-V2 for the vertical seepage test and on the RPP-H2 for the horizontal seepage test. A load cell and a piston apply a constant load on the sample. A flexible membrane in the top piston allows to apply an air pressure between the membrane and the wall of the piston, which, in turn, ensures an efficient seal around the square top piston. An LVDT allows a continuous monitoring of the sample height allowing to calculate the evolution of void ratio during the course of testing.

An automated acquisition system monitors temperature, load, height and water flow.

Legend :

TPP-V2 : **T**op **p**orous **p**late for **v**ertical outflow

BPP-V1 : **B**ottom **p**orous **p**late for **v**ertical inflow

LPP-H1 : **L**eft **p**orous **p**late for **h**orizontal inflow

RPP-H2 : **R**ight **p**orous **p**late for **h**orizontal outflow

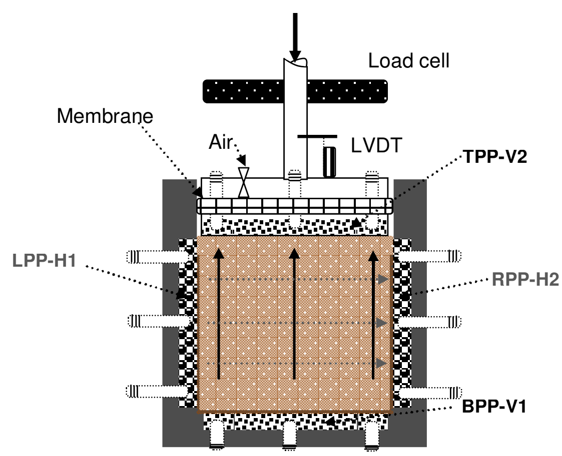

Figure 2. Cubical permeameter

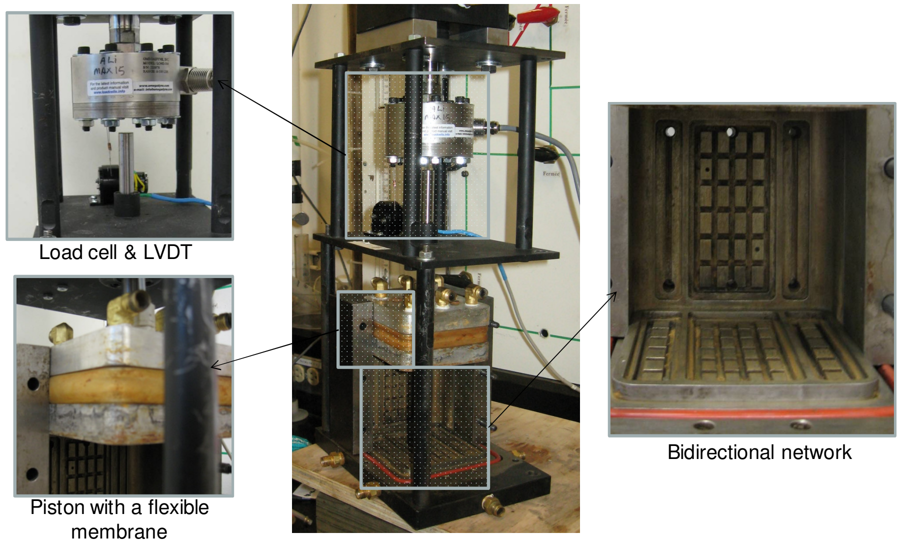

Figure 3. Photography of the experimental device

2.2 Preferential flow path

The following section presents the way to eliminate preferential flow in the porous plates parallel to the flow.

The permeability of porous stone is high compared to that of the soil sample, which has the effect of diverting the flow lines. As shown in Figure 4, during the vertical seepage test, the LPP-H1 and RPP-H2 porous stones affect the flow lines. The same problem occurs during the horizontal seepage test due to the presence of porous elements in the BPP-V1 and the TPP-V2 plates.

To remedy this problem, the porous stones parallel to the flow lines must be temporarily sealed. A solution with a high concentration (35 % w/w) of bovine gelatin is used for this purpose (Figure 5). This product has already been used in geotechnical studies for undisturbed sand sample (Robichaud S. 2004 and St-Laurent J.F. 2007). However, the concentration was increased to obtain a melting point near 30 °C, which allows the experience to be done at room temperature, i.e 20 °C. In the case of very low permeable clays, where the test may last more than a month, the permeability test should be carried at a lower temperature to increase the effectiveness of gelatin bovine.

2.3 Application of the bovine gelatin in the vertical network flow

A manual application of bovine gelatin in the LPP-H1, in the RPP-H2 and on the filter paper (Figure 6) is done prior to compacting the sample inside the cubical cell. To ensure a visual quality control, liquid color is added to the gelatin. On all the other vertical walls without any porous elements, a thin layer of silicone grease is applied to minimize flow at the soil-wall interfaces.

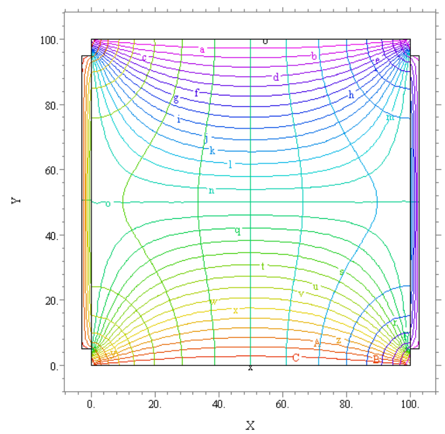

Figure 4. Flow lines affected by the porous stone

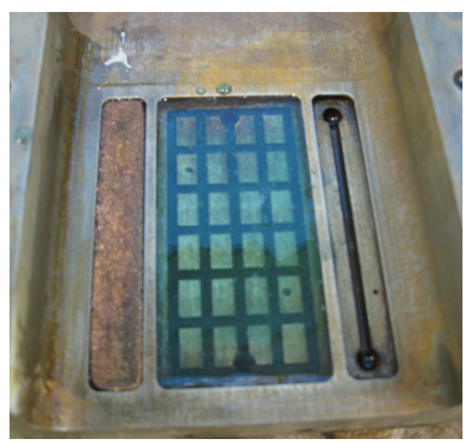

Figure 5. Application of the bovine gelatin to seal the porous stone

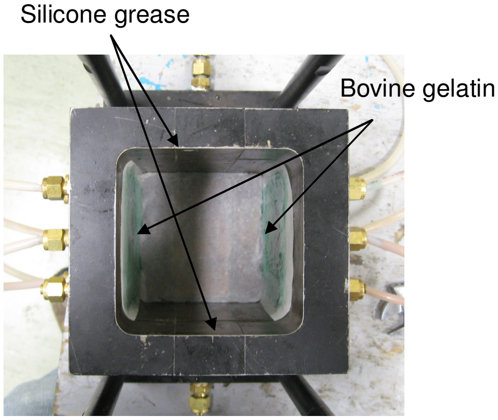

Figure 6. Cubical cell before the soil compaction

3 TESTING PROCEDURE

3.1 Compaction of the sample

Once the cell is assembled, the sample can be compacted. Two methods of compaction have been selected for this study: the proctor hammer and vibrating hammer. Till is compacted in four different layers to a specified density. A scarification between each layer is done.

3.2 Vertical permeability test

After compaction of the sample, vertical permeability test can be conducted. A maximum hydraulic gradient of 13 cm/cm is applied in the upward direction (BPP-V1 to TPP-V2).

3.3 Heating and washing the vertical porous stones

After completion of the vertical seepage test, sealed porous elements in the LPP-H1 and RPP-H2 plates must be done without dismantling the cell. A heating plate is used for this purpose. The internal temperature of the mold must be greater than 30℃ in order to turn the solid gelatin into a liquid of approximately the same viscosity as water.

Before flushing the liquid gelatin with warm water, all other inputs of water must be closed. That procedure is done to ensure that water doesn't circulate within the sample, but is restricted to the porous element only (Figure 7). Next, a cleaning system with a tank (27 liters) of hot water is used to fully flush out the remaining gelatin in the porous stones in opposite sides of the permeameter. Each side is cleaned by a 60 ℃ water circulation during one hour.

3.4 Injection of gelatin in the horizontal porous stones

A liquid gelatin solution is then injected in BPP-V1 and in TPP-V2 porous elements with a syringe. Water in these stones is replaced by the gelatin considering that the viscosity of gelatin solution is slightly higher than that of water.

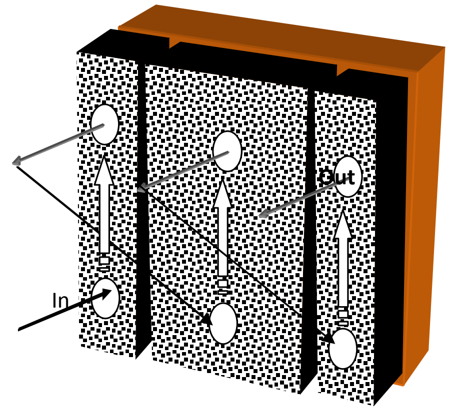

Figure 7. Method used for washing the porous stone

The whole device is left for 12 hours in order to let the temperature return to room temperature. Otherwise, the value of hydraulic conductivity would be influenced by a change in the water viscosity during the test.

3.5 Horizontal permeability test

After this step, test with horizontal seepage can be done by applying a maximum hydraulic gradient of 13 cm/cm.

After the permeability test with horizontal flow is complete, the final dimensions of the sample and moisture content are quantified to back calculate the void ratio and degree of saturation of the sample (Figure 8).

The effectiveness of the gelatine injection of horizontal stones (BPP-V1 and TPP-V2) and of the removal of gelatine in the vertical stones (LPP-H1 and RPP-H2) can also be confirmed visually once the cell is dismantled. Figure 9 shows that water placed on the porous element sealed by gelatine remains on the plate, unable to penetrate into the plate confirming thus that gelatin introduced by the injection process is indeed an efficient sealant.

4 TYPICAL RESULTS

4.1 Raw data

As presented in Figure 10, the air temperature is held at a constant temperature throughout the test. Thus, no correction for modification of the water viscosity is needed. The sample is compacted in a dense state, in order to minimize axial deformation. However, if the sample is in a loose state, the hydraulic gradient for vertical flow and sectional area for horizontal flow must be corrected if settlement is important. The volume of water entering and leaving is recorded on a continuous basis. Monitoring the degree of saturation on mass balance was too inaccurate, which does not allow its continuous monitoring. However, the degree of saturation is known at the initial and final states which allows to approximate its evolution. In the example shown on Figure 11, the initial degree of saturation was 65% while the final degree of saturation was 67%.

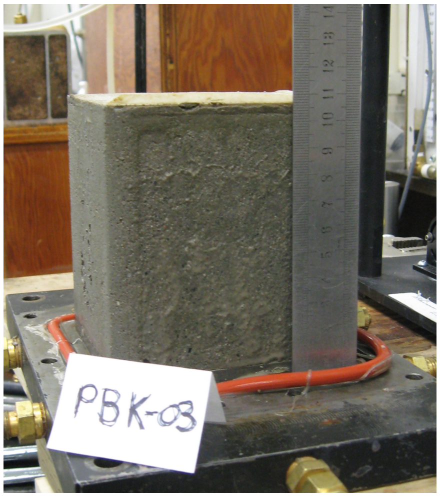

Figure 8. Unmoulding of the sample

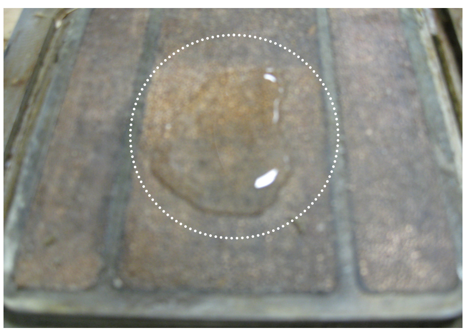

Figure 9. Visual confirmation of the efficiency of the gelatin injection

4.2 Data analysed

As discussed before, the water head is constant at both ends, which creates a constant hydraulic gradient (Figure 11). The flux is equal to the slope of the curve of volume of water divided by the sample's cross-sectional over time. By dividing the slope of this curve by the hydraulic gradient, the value of hydraulic conductivity is obtained as stipulated by Darcy's law.

5 VALIDATION

The preliminary validation is obtained by comparison of the hydraulic conductivity values obtained with the cubical permeameter and a flexible wall cylindrical permeameter. These latter tests were conducted in accordance with ASTM D5084-03 standards.

The samples were set up under similar conditions by vibro-compaction in several layers. In the case of the flexible cell wall, 5 layers of 40 mm were made while in the cubic cell, the number and size of the layers were respectively 4 and 25 mm. In both cases, a scarification between each layer was carried out to avoid the creation of a preferential flow between each interface. The results shown on Figure 12 indicate that the relationship between K and void ratio was the same for both types of testing equipment. This, in turn, suggests that preferential seepage in the rigid cubical permeameter is negligible and that the proposed testing procedure using bovine gelatin is adequate.

In order to confirm the efficiency of the gelatin, several permeability tests were carried out the same sample, but with different hydraulic gradients. As indicated in table 1, K varied between 1,7 x 10^{-9} and 2,0 x 10^{-9} m/s for vertical flow with i increasing from 7 to 13. For the horizontal seepage, K varied between 1,8 x 10^{-9} and 2,4 x 10^{-9} with i decreasing from 13,0 to 8,8. The increase in the degree of saturation may explain the difference between these two K-values.
Darcy's law is thus verified, indicating that seepage occurs essentially through the soil sample.

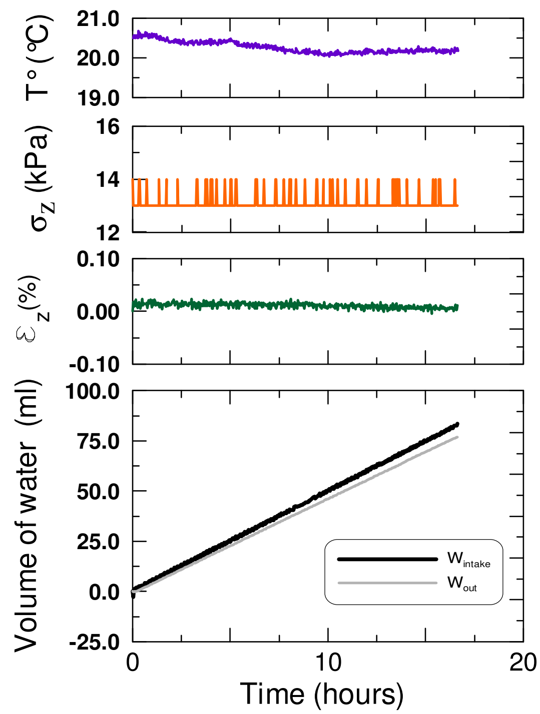

Figure 10. Raw data

6 DISCUSSION

In Figure 13, it is possible to compare the values of r_K obtained in this study compared to data in the literature for different types of soil. The results from the new testing device follow the general trend reported so far by different studies.

6.1 Disadvantage of this device

As nothing is perfect, this method also has two main disadvantages. First, the injection of gelatin during the test, the heating of the cell and the flushing of porous stones make the use of the new permeameter more tedious than a conventional permeability test. Moreover, the first prototype cannot yet apply a pressure to the water higher than 300 kPa, which is needed to fully saturate compacted till samples.

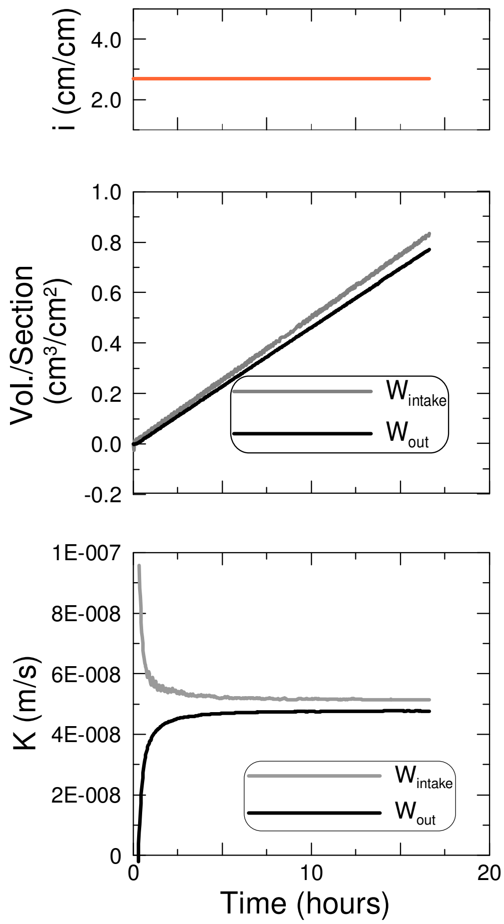

Figure 11. Data analyzed

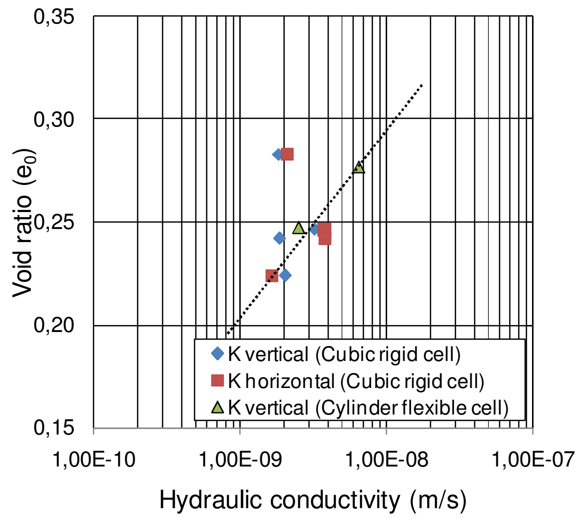

Figure 12. Comparison of the hydraulic conductivity obtained by two types of device for sample setting up at a similar void ratio

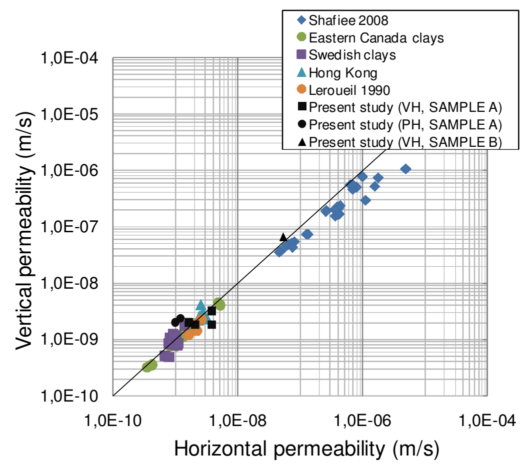

Figure 13. Comparison of the inherent hydraulic conductivity anisotropy ratios obtained by the cubic cell and other experimental devices

Table 1. Relationship between hydraulic gradient and hydraulic conductivity for a till

	Vertical seepage			Horizontal seepage	
	1	2	3	1	2
K (m/s)	2.0E-09	1.7E-09	1.8E-09	1.8E-09	2.4E-09
i (mm/mm)	7.0	10.0	13.1	13.0	8.8

7 CONCLUSIONS

A new cubic permeameter was designed to obtain the permeability ratio on the same sample. A special testing procedure was developed to limit seepage trough the inactive porous stones, i.e. the porous stones parallel to the seepage flow. Bovine gelatin, solid at temperatures less than 30 °C was used and proved to be highly efficient in sealing the inactive porous elements. Heating at 60 °C allows to remove the liquid gelatin without the need of dismantling the cell. A new percolation test can then be conducted on the same sample but in a different direction. Preliminary tests on a compacted glacial till have shown that the hydraulic conductivity values compared well to those obtained from tests using a flexible wall permeameter. The k anisotropy was found close to unity, which was also reported by other studies on similar soils.

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