A new Hydraulic profiling tool including CPT measurements

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ABSTRACT: The Perméafor is an in situ soil testing device developed in the early 80's. The probe has a conical shape and is pushed or hammered into the ground using a conventional drill rig. The tool is advanced through the subsurface at a constant rate while water is injected through a screen at the mid level of the probe. A quick estimate of the permeability profile of ground layers encountered can be derived. . The permeability profile obtained is complemented by a penetration curve (elapsed time for 20 cm driving depth) in order to evaluate the quality of the soil. The device has been recently modified to include a piezocone tip. This paper presents calibration of this test with water tests performed in laboratory and in situ and the use of the new version of the device during a dike survey campaign and comparison of this test with pumping tests, Lefranc tests and standard electric cone penetration testing.

1 INTRODUCTION

The Perméafor was developed by the Public Works Research laboratory (LRPC) of Strasbourg in the early 80s and patented in 1986. This hydraulic profiling tool (HPT) provides a quick estimate of the in-situ profile of soil permeability. It gives an order of magnitude of soil permeability in a quasi-continuous way (approximately every 20 cm). The permeability profile obtained is supplemented by a penetration curve (for 20 cm) to qualitatively assess the resistance to penetration of soil and identify heterogeneities of the ground mass. It proved to be an efficient tool for the geohydraulic characterization of waterway infrastructure. This paper presents the equipment developed, the test method and analysis of results and a compilation of results that has led to a correlation with conventionally measured permeability.

2 EQUIPMENT

2.1 *Test principle*

The test consists of the measurement of the flow of water injected through a porous tip under a constant hydraulic head, at the level of the screen. The geometry of specially designed tip allows continuous testing during penetration without use of packers (Ursat, 1992).

2.2 *Test equipment*

In addition to a drill rig, drill pipes, adaptation head and connecting tubes, the equipment is composed of the following (Figure 1a):

- Perméafor porous tip,
- measuring assembly with flow meters, pressure and displacement transducers and bypass valves,
- data logger for acquisition on a laptop equipped with software for display of flow and average flow in real time.

Both flow meters cover a range from 0.1 to 180 l/min with an accuracy of +/- 0.5%. The whole system works with a pressure regulator with hydrostatic balance to apply hydraulic heads between 3 and 5 m with an accuracy of +/- 5 mm. H_e is the pressure measured at the pump.

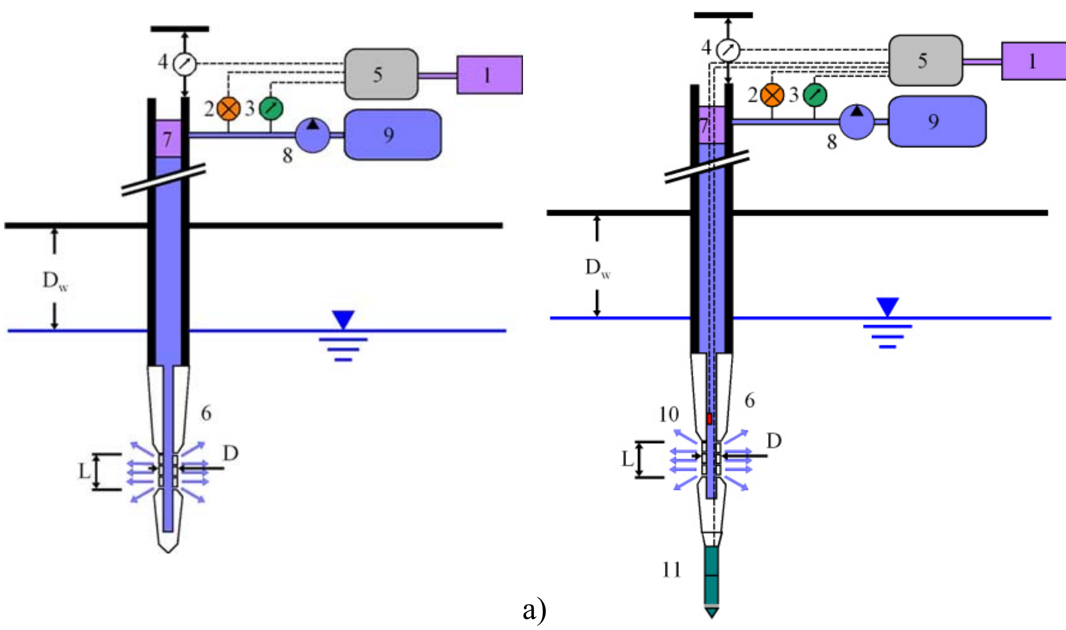


Figure 1. Permeafor HPT test equipment (1: Laptop, 2: flow meter, 3: pressure sensor; 4: displacement transducer; 5: data logger, 6: Permeafor tip; 7: water head; 8: pump; 9: water tank; 10: pressure transducer; 11: electric cone penetrometer with pore pressure measurement)

The shape of Perméafor HPT porous tip ensures proper sealing around the screen and prevents leakage parallel to the axis of the borehole. Water spreads out radially into the soil and a well defined cylindrical field of flow is created determined by the pressure at the borehole wall and measured by the rate at which water is injected. Other benefits of the Perméafor HPT test are its ability to perform a test during penetration without prior casing, and due to the low height of the cylindrical cavity, to make a number of measures (5 per meter or more) (Ursat, 1995). The maximum outside diameter of the probe shown in Figure 1a is 60mm and diameter of the porous screen *D* is 44mm.

2.3 *Evolution*

In order to facilitate analysis of Perméafor HPT tests, a new design of the tip which incorporates a piezocone was needed (CEN/ISO, 2005). This would allow access to the CPT soil classification charts by Robertson (1990), estimation of soil compacity and identification of areas of low saturation. It is then possible to propose more robust correlations as validated by several measurements on the hydraulic and mechanical behavior of materials tested. These developments required modifications to the existing device. It was therefore decided to add a pressure sensor close to porous screen and an electric cone penetrometer with pore pressure measurement under the porous tip and completely renew the data acquisition (Figure 1b).

3 TEST

3.1 *Experimental Protocol*

During the Perméafor test, the HPT tip is driven into the ground in 20 cm increments with the help of a drill rig using a conventional hydraulic hammer. When the screen is in the soil, the injection starts and is done continuously throughout the duration of the penetration. When penetration is stopped, the flow is recorded versus time for 10s and then penetration is continued.

3.2 *Analysis results*

The derived parameter computed from measurements and equivalent to permeability is:

$$P_k = \frac{Q}{H'} \tag{1}$$

with:
Q: outflow,
H': corrected water head

$$H' = H_e + D_w - dH(Q) \tag{2}$$

where:
H_e: imposed water head,
D_w: water table depth,
$dH(Q)$: pressure losses in the circuit, depending on the outflow

Error calculation using values given above leads to the following conclusions: the error in P_k during a test at constant load is about 3% and may become more important if the corrected water head becomes too low. This can occur for very permeable soils because, when the flow increases, the losses in the injection circuit increases for shallow water table i.e. D_w is close to 0 or confined aquifer for which D_w <0.

Thus the ratio *Q/H'* is generally capped at a value of 5.10^{-3} m²/s, corresponding to highly permeable soils.

3.3 *Factors of influence*

The outflow is a function of soil permeability and the pressure imposed. The latter depends on the available water head, groundwater depth and losses in the injection circuit (flow meter, valves, tubes, porous screen). The pressure losses are a function of flow and are measured by prior calibration. This test therefore requires a correction which will not be detailed in this paper (see Ursat, 1992).

The short test time usually does not lead to establishment of a permanent flow. Thus, the ratio Q/H' is calculated for a value less than 5.10^{-7}m²/s.

3.4 *Correlation with permeability*

The literature indicates an expression of flow:

$$Q = \frac{2.\pi.{}^{L}\!/\!_{D}}{\ln\left({}^{L}\!/\!_{D} + \sqrt{L^2/D^2+1}\right)}.K.H.D \qquad (3)$$

The formula would theoretically quantify the permeability K in m/s of crossed horizons from the ratio Q/H.

$$K = \alpha.P_k \qquad (4)$$

with a value of $\alpha = 2.8$ for *L/D* = 1 and *D* = 0.05 m (see Figure 1).

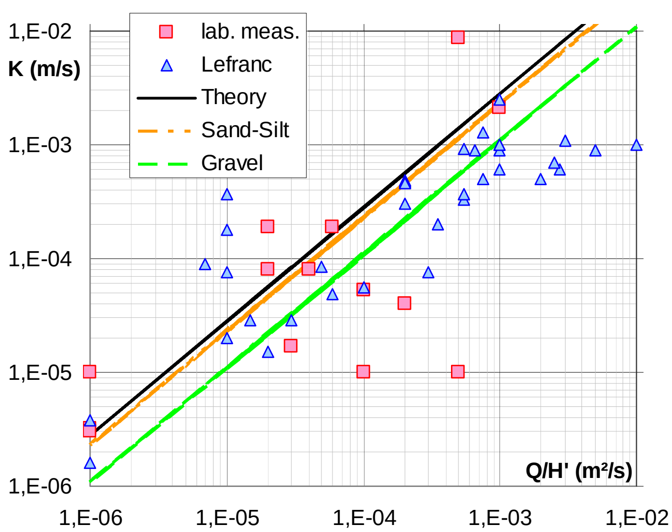


Figure 2. Correlation between measurements of the permeability coefficient K obtained using different methods and Q/H '

Figure 2 shows the correlation obtained from Lefranc tests or permeability tests conducted in laboratory using Proctor molds for more than a dozen sites. They were supplemented by a calibration test in a calibration chamber on different materials of known geohydraulic characteristics. These results have identified an experimental value of this ratio close to 2.3.

4 CALIBRATION TESTS

This research was supported by Electricité de France responsible for numerous dikes and dams in relation with power plant activity. Since several years, Rhine left bank dikes are facing leakage. An in depth survey of the dikes was made including CPTu, Lefranc tests, Perméafor HPT and laboratory tests (particle size distribution, permeability test). Piezometers were also installed. All information collected has resulted in a set of parameters that could be compared to Permeafor results. The results shows good correlation of Perméafor curves with the cone penetration tests (Figure 3).

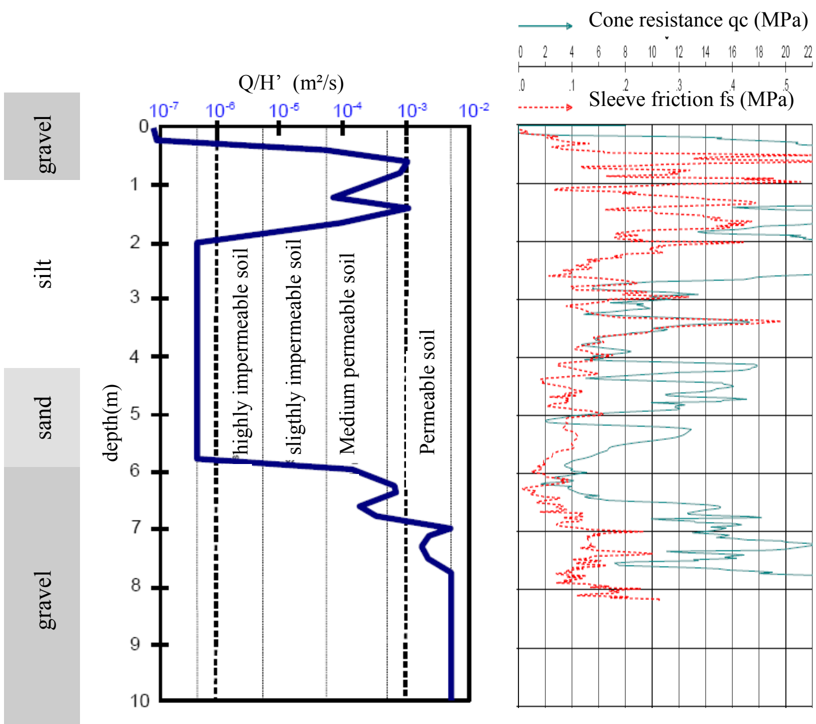


Figure 3. Ratio Q/H' log and CPT for profile number 5

The dike core is composed of mixed gray silt and Rhine gravel are clearly identified with the contrasts of permeability observed at a depth of about 2 m and 6 m. Analysis of core samples have helped ensure the relevance of Permeafor test in locating these layers.

Calibration tests have also been carried out on two trial embankments built in the Centre d'Expérimentation Routière (CER) facilities in Rouen. The general object of the experiment was to test the new design of the Perméafor HPT for consistency with itself and against other methods.

Figure 4 show the geometry of the trial embankment made of Rhine alluvial gravel (0/64 mm) including two cells; the compacted one built in 11 layers compacted to reach 95% of Proctor optimum density and the non compacted one constructed in 6 layers with a final density of 85% of Proctor optimum density (Figure 6b).

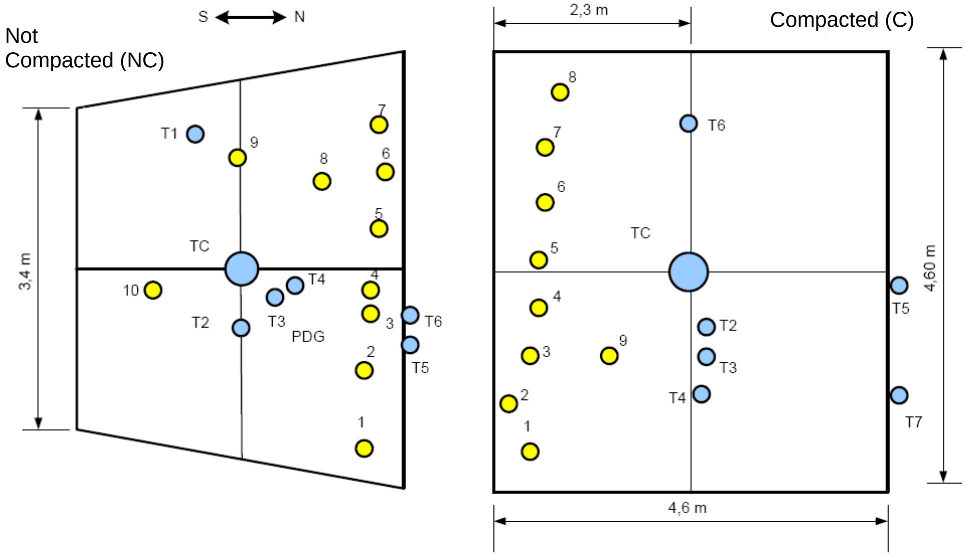
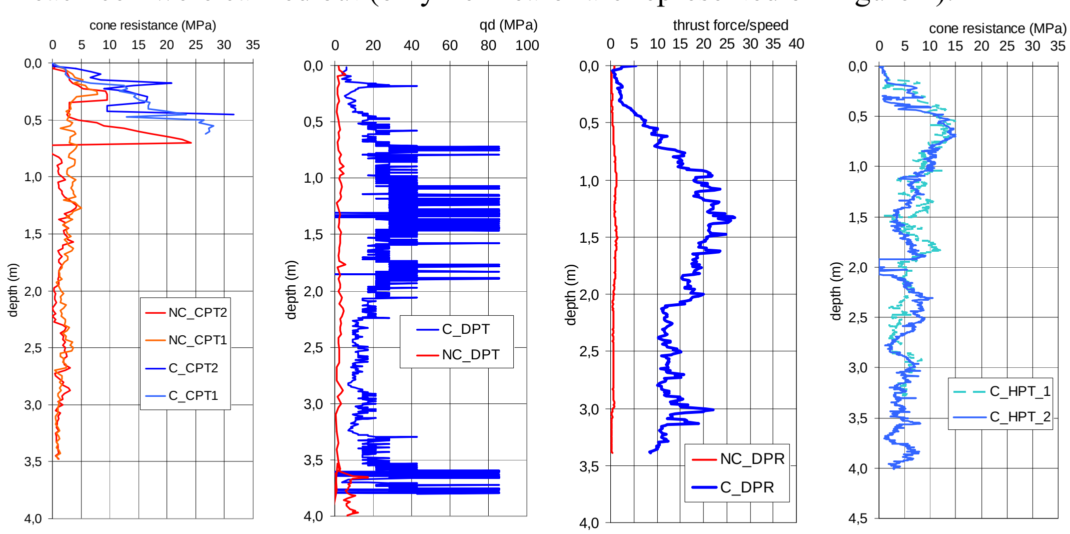


Figure 4. Top view of trial embankment

Cells were wrapped in a geosynthetic liner and equipped of plastic tubes (marked T on Figure 4). Pumping tests carried out in the two cells gave average permeability coefficient of $3.65.10^{-1}$ m/s in compacted cell and $2.30.10^{-1}$ m/s in uncompacted cell.

Eighteen Perméafor HPT profiles, four CPTu and two dynamic probing tests, half in each cell were carried out (only Perméafor are represented on Figure 4).



(a) (b) (c) (d)

Figure 5 Profile (a) CPTu, (b) dynamy probing, (c) drilling parameter recording, (d) Permeafor CPT (C for compacted and NC for uncompacted cell)

Figure 5 shows these different profiles. Classical CPT were difficult to realize in the dense and coarse gravel therefore they were stopped at 0.6 m (Figure 5a). Gentle hammering of Perméafor probe has permitted to penetrate the gravel without destruction of electric cone and to obtain a cone resistance profile (Figure 5d). The different type of penetration test profiles and the thrust force measured using drilling parameter recording normalized by the feed speed are very consistent.

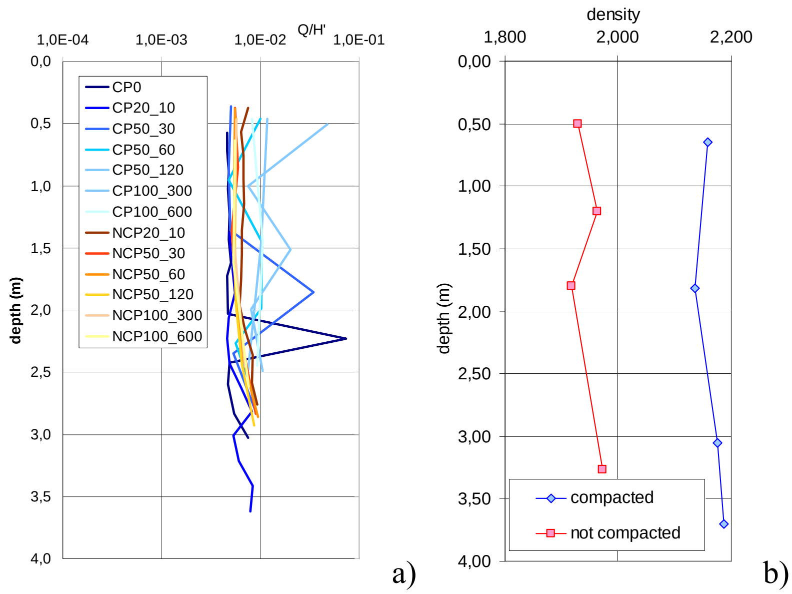


Figure 6. a) Q/H' profiles and b) density profiles for both cells

Figure 6a summarizes the different values of permeability tests performed on the site. Different lengths between injection phases and different injection times have been tested. For this well graded soil, there are almost no differences between compacted and uncompacted cells even if the rearrangement of grain particles seems to create scattered profiles for compacted cell. However tests realized in compacted cells give lower values. Ratio between permeability coefficients K obtained by pumping test and Q/H' ratio obtained from Perméafor tests are close to the values observed in Figure 2.

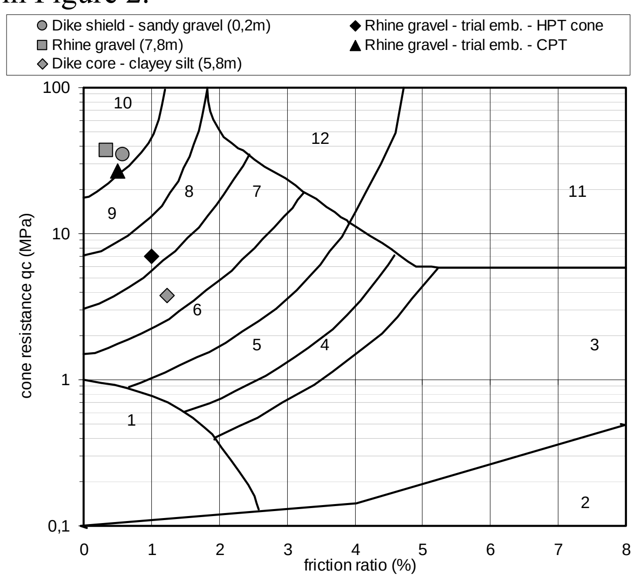


Figure 7. Robertson chart (1990) Rhine dike Profile 5,6 and trial embakment (1. Sensitive fine-grained soil, 2. Organic soil, 3. Clay, 4. Silty clay to clay, 5. Clayey silt to silty clay, 6. Sandy silt to clayey silt, 7. Silty sand to sandy silt, 8. Sand to silty sand 9. Sand 10. Sand to gravelly sand, 11. Very stiff fine-grained soil, 12. Overconsolidated or cemented sand to clayey sand) (EN/ISO, 2002; 2003)

Interpretation of CPTu data was based on chart proposed by Robertson (1990) (Figure 7). This analysis has led to a relatively accurate classification of materials encountered according to soil profiling realized from cores samples obtained from core drilling performed close to CPT profiles location (2m along the axis of the dike). In a first approach, the use of hammering or vibrodriving the cone has an influence but this was not the object of this experiment.

This study has validated the new design of the probe and the pertinence of the results. The next stage of this research is to insert a layer of silt, 1m thick at mid height of the cells to investigate the ability of the new probe to give information when the probe penetrates through the contact zone.

5 CONCLUSIONS

The Perméafor HPT is a device developed and used by the Scientific and Technical Network of Department of Environment, Energy, Sustainable Development and Spatial Planning. The potential advantages of this new HPT are both technical and economic:

- variation of permeability can be identify with accuracy,
- possible classification of soil using existing CPT-based charts and other relationships,
- speed in execution.

The HPT allows the development of continuous permeability logs with qualitative analysis leads to an initial diagnosis of the structure of dikes (Featured in leakage levels mainly). This device reliably determines the transition zones with high gradient (i.e. contact between silt and gravel for example), which are preferential areas for the development of internal erosion. Its rate of penetration made it a device with "great performance" given the number of water tests carried out conventionally.

In the field of dikes and canals, the number of existing works is considerable. The high stakes associated with the sustainability of these existing structures, particularly against the mechanisms of internal erosion, have led the Strasbourg LRPC to consider the evolution of the Perméafor to obtain quantitative geotechnical parameters, and secondly reliable preliminary diagnosis method of the internal structures of dikes.

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