Ground water monitoring with the BATÒ-system

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Pore pressure is an important parameter for the mechanical behaviour of soil. With the BATÒ-system it is possible to define this parameter in the field and to conduct several other ground water measurements. This publication describes this method, its possibilities and compares it to other kinds of pore pressure sensors.

Introduction

The effective stress in the soil defines the mechanical behaviour of soil. According to Terzaghi these stresses can be described as:

$$s = p + s_k \qquad (1)$$

in which

s = stress [Pa]
s_k = effective stress[Pa]
p = pore pressure [Pa]

Formula (1) shows that with a given stress in the soil, the mechanical behaviour is strongly influenced by the pore pressure present in the soil. Measuring the pore pressure is especially important in load increases in low permeable soils where the danger of sliding can occur. As well as in temporary or permanent changes in pore pressure through which the effective stresses increase causing permanent deformations.

The method mostly used to determine the pore pressure is the piezometer tube. However, this is less suitable for soils with a low permeability like clay, peat and silt. In these soil types the gauge has a very long reaction time.

Therefore, a piezometer or pore pressure meter is preferred in this type of soil. This type of sensor measures the pore pressure locally in the soil in which a very small water movement is necessary, resulting in a far quicker reaction time in less permeable soils.

Every pore pressure sensor consists of two main parts:

1. The filter: a filter that is water permeable picks up the effective stress. This results in a space where the pore pressure can be measured. To function correctly attention has to be paid to the pore size of the filter in comparison to the grain sizes of the soil.

2. The measuring element: the pore pressure is measured with a pressure sensor based on different measuring principles. Possibilities are for example: vibrating-wire sensors, semiconductors, resistance strain gauges or capacitive pressure sensors.

The BAT®-system for pore pressure measurements

The BAT®-system has existed now for about ten years and has reached its third generation, but has been relatively unknown in the Netherlands. The system can be described as follows. The key element is the filter tip, which after being filled with de-aired water, is pushed down to the desired measurement level. The filter tip is pushed down with coupled 1-inch gas pipes, so sounding-pipes are not used. Through the gas pipes the measuring element is subsequently connected to and disconnected from the filter tip.

Measurements can be done in three ways. The simplest way strongly resembles measuring the water height in a piezometer tube. The pore pressure measurement is then effected manually. The sensor is lowered down the gas-pipe and coupled to the filter tip. After a few minutes the value has stabilised and is then saved in the digital memory of the sensor. Afterwards the sensor can be disconnected and the whole procedure can be repeated at the next location.

An alternative method is to provide every filter tip with a sensor (with standard integrated data logger) for a longer period. The measurement results are then read out from the sensors periodically. Because of the continuous registration the pore pressures are measured more frequently. This method simplifies the interpretation of the measurements, because it is easier to separate trend-behaviour from incidental extreme values.

The most advanced method is to provide each filter tip with a sensor that is interconnected by one single cable. In this case the sensors form a digital network in which all data are directly available. Reading out of the data loggers on a weekly basis is then not necessary anymore and all data are immediately available at the right place.

Comparing the qualities of piezometers

Location**:** a pore pressure measurement with the filter tip is always done using a gas pipe to ground level. So it is always possible to detect accurately where and at which depth the measurement is done. The piezometer that is connected to cone bars and is regained after use, has this same advantage. Knowing the depth of the measurement location is important with terrain consolidation. If the gas pipe or sounding-cone will be an obstacle, it is better to use a single-use type of pore pressure sensor. In this case only a cable leads to the ground level.

Separation**:** the stability of the measuring element in a piezometer is of great importance, because a measurement in an unfavourable environment has to be done reliably and accurately for a longer period. Therefore, the measuring elements of the pore pressure sensors are mainly chosen for reliability and stability. Examples are vibrating-wire sensors or resistance strain gauges integrated in semi-conducting material. In practice circumstances often arise in which the results deviate considerably from the expectations and the question arises whether the measuring element functions correctly. With the BAT®-system the measuring element is connected to the filter tip. This connection can be made hundreds of times without problems.

Therefore it is possible to replace or to control the scaling factor and the zero point, by which the insecurity concerning the rightly functioning of the measuring element is excluded. This separation can also be realised using a pressure switch in the pore pressure sensor. The pressure measurement then takes place on the surface level. It is only determined in the sensor whether the pressure created on the ground level is greater or similar to that in the ground.

Installation**:** Pushing down the pore-pressure sensors in low permeable soils results in deformations in the soil which lead to a considerable, but temporary, increase of pore pressure. This may overload the measuring element and cause it to function inaccurately. This risk can be eliminated by measuring the pore pressure during pushing down the sensor or, as with the BAT®-system, connecting the measuring element to the filter after placement. The filter tip is barely sensitive for the consequences of a possible pressure-overload.

Synthetic**:** a less known problem with pore pressure measurements is the so-called galvanising action that arises from the usage of different metals. In the soil this can lead to corrosion and formation of gas. Producing the pore pressure meter by using only one type of metal can diminish this problem considerably.

Another solution is a filter tip of plastic that totally solves the problem. The mostly used filter tip for the BAT®-system is therefore made of a synthetic. If the stainless-steel filter tip is used because of the large soil resistance, corrosion danger also develops. The firstly connected gas pipe then also has to be of stainless steel to minimise the chance of corrosion in the surroundings of the filter.

Absolute: it is common use to correct the pore pressure measurement for variation in the air pressure. This is done because the air pressure takes effect upon stress in the soil as well as upon the pore pressure so that the effective stress is less influenced.

The simplest method is a relative measurement in which a thin compensation air hose is connected with the measuring element and the open air. So the difference between the pore pressure on one side and the air pressure on the other side of the measuring element can be directly determined. However, this method is not very popular with pore pressure sensors. The compensation hose can clog up by condensation and the measuring element can be affected by moisture. Usage of hygroscopic or semi-permeable materials diminishes these problems.

However, when measuring the pore pressure absolute pressure sensors are strongly preferred to relative measuring elements. The air pressure is measured with a separate pressure sensor. An example of a measurement is given in figure 1. The air pressure at sea level is on average 1013 mbar, but can vary strongly causing a large error if the measurement is not corrected as figure 1 shows. Variations of about 100 mbar (≈ 1 meter water column) are possible during long-term measurements.

Other ground water measurements

Consolidation coefficient c_h: installing a pore pressure meter in low permeable soils gives a temporary increase of the pore pressure. This increase can be used to determine the local consolidation coefficient. The measurement has to be started directly after installation. Using a mathematical model shows that the half-time of the pressure-increase is connected with the consolidation coefficient. A good estimation according to Torstensson [1] is:

$$c_h \approx \frac{r_o^2}{t_{50\%}} \qquad (2)$$

c_h = consolidation coefficient [m²/s]
r_o = filter ray [m]
$t_{50\%}$ = pressure half-time [s]

Applying this determination is especially meaningful in measurements during the filling up of terrains with less load bearing capacity. Then the usage of pore pressure meters is shown to its full advantage. After the start of the task the settlement prognosis can then be improved with the surplus information. After placing the load a second measurement of the consolidation coefficient can be done with the dissipation of the pore pressure. The c_h measurement according to formula 2 can therefore be well controlled (see also *figure 4*).

Permeability k: the filter tip provides the opportunity to measure the permeability *k* of the soil. In this case the filter tip is connected to a container with another pressure than the local pore pressure, as can be seen in figure 5. In the case of a lower pressure, water is absorbed. In higher pressure water is injected into the soil. The pressure lapse as a function of the time has a univocal relation with the permeability *k* of the soil. This relation is according to Bengtson [2]:

k = permeability [m⁴/Ns]

$$k = \frac{V_0\ p_0}{F\,t}\left(\frac{1}{p_1 p_0} - \frac{1}{p_1 p_t} + \frac{1}{p_1^2}\left(\ln\left(\frac{p_0 - p_l}{p_0}\frac{p_t}{p_t - p_l}\right)\right)\right) \qquad (3)$$

p_0 = pressure in the container at the start of the test [Pa]
p_t = pressure in the container as function of time [Pa]
p_l = pore pressure in the soil [Pa]
t = time [s]
F = flow factor of the filter tip according to Horslev (3) [m]
V_0 = volume of the container [m³]

Figure 2 shows several lines for different values of the initial pressure in the container. The measuring range of the permeability *k* of the filter tip runs from 10^{-12} to 10^{-5} [m/s]. The smallest value is controlled by the maximal time range of a measurement, while the largest value is limited by the flow resistance in the coupling of the filter tip to the container.

Another restriction is the time resolution of the sensor. The large permeability should therefore be measured with a small pressure difference between the container and the local pore pressure. The resistance of the coupling is then minimal and the pressure can be correctly defined. This effect can be seen in figure 2. With the lowest initial pressure the pressure as a function of time suddenly goes up. The measured value of the permeability is then strongly dependent on the moment on which the coupling with the filter tip is made and cannot be defined precisely (see also *figure 6a, 6b and 7*).

Water samples**:** the filter tip can also be used to take ground water samples. The method is the same as with the permeability measurement. Obviously the initial pressure has to be lower than the pore pressure. The pressure sensor which is coupled to the container is now optional, but offers more control during the carrying out of the test. If the intake is long enough, the pressure in the container is the same as the pore pressure. The water sample, including the present soil gas samples, is disconnected under this pressure after which the sample can be analysed. This method makes it possible to take samples without external pollution and without air contact.

The samples are of an extremely constant quality, because the method is less sensitive to human mistakes. Noteworthy is that before placement the filter tip is with clean water. The intake should therefore be done 1 to 2 times to get a representative ground water sample.

Hydraulic fracturing**:** Formula 1 indicates that the effective stress becomes zero when the pore pressure is the same as the stress in the soil. The filter tip can be used in less permeable soils to determine this value of the pore pressure. The measurement is done as a permeability test where the container is filled with water and gas with a considerable overload. As long as the pressure during the injection of the water is larger than the effective stress (in horizontal as well as vertical direction), the permeability will be enlarged by ”*cracks*” in the soil. After the pressure has been reduced, the soil will close and the curve will vary as with normal permeability. In the pressure-time measurement this transition point is clearly visible (see figure 7).

Ground water flow**:** The filter tip also offers possibilities for research for ground water flow. This is possible by injecting a controlled amount of liquid with a chemical additive. At other locations ground water samples are hereafter taken and researched for the chemical additive. This maps the flow of the water.

Conclusion

The BAT®-system is an interesting alternative for measuring pore pressures, which up til now not much attention has been paid to in the Netherlands. It is a high-quality and economic method with a lot of extra possibilities. Besides applications in foundation engineering, the system also offers unique possibilities in the field of environmental research.

References:

1 Torstensson, B-A. 1978, The pore pressure probe. *Proc. Geoteknikkedagen*, pp. 34.1-34-15, Tapir forlag, Oslo, Norway.

2 Bengtsson. P.E. 1984. Personal communication

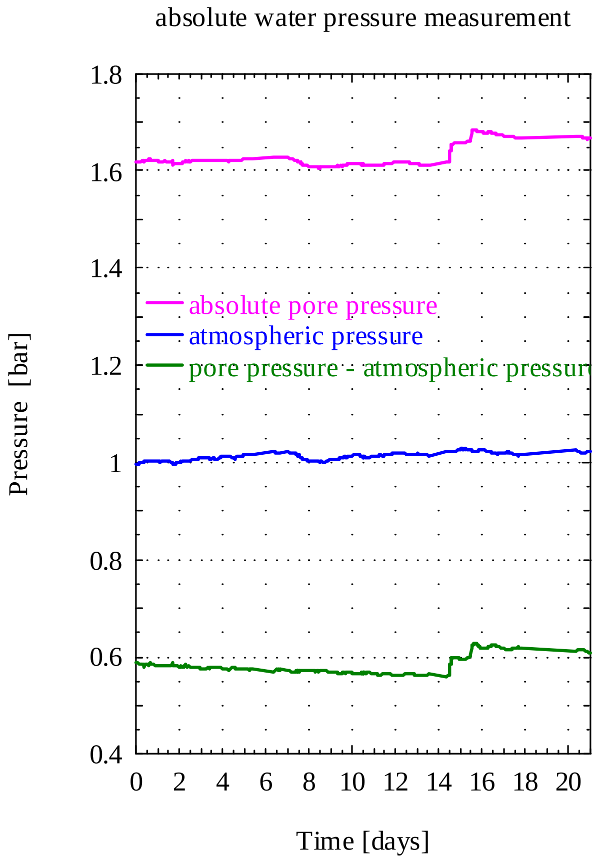
3 Horslev. M.J. 1951. Time lag and soil permeability in ground water observations. *Corps of Engineers*. Waterways Experiment Station. Vickburg. Mississippi. Bull. 36,50 pp.

More data about different kind of piezometers can be found in:

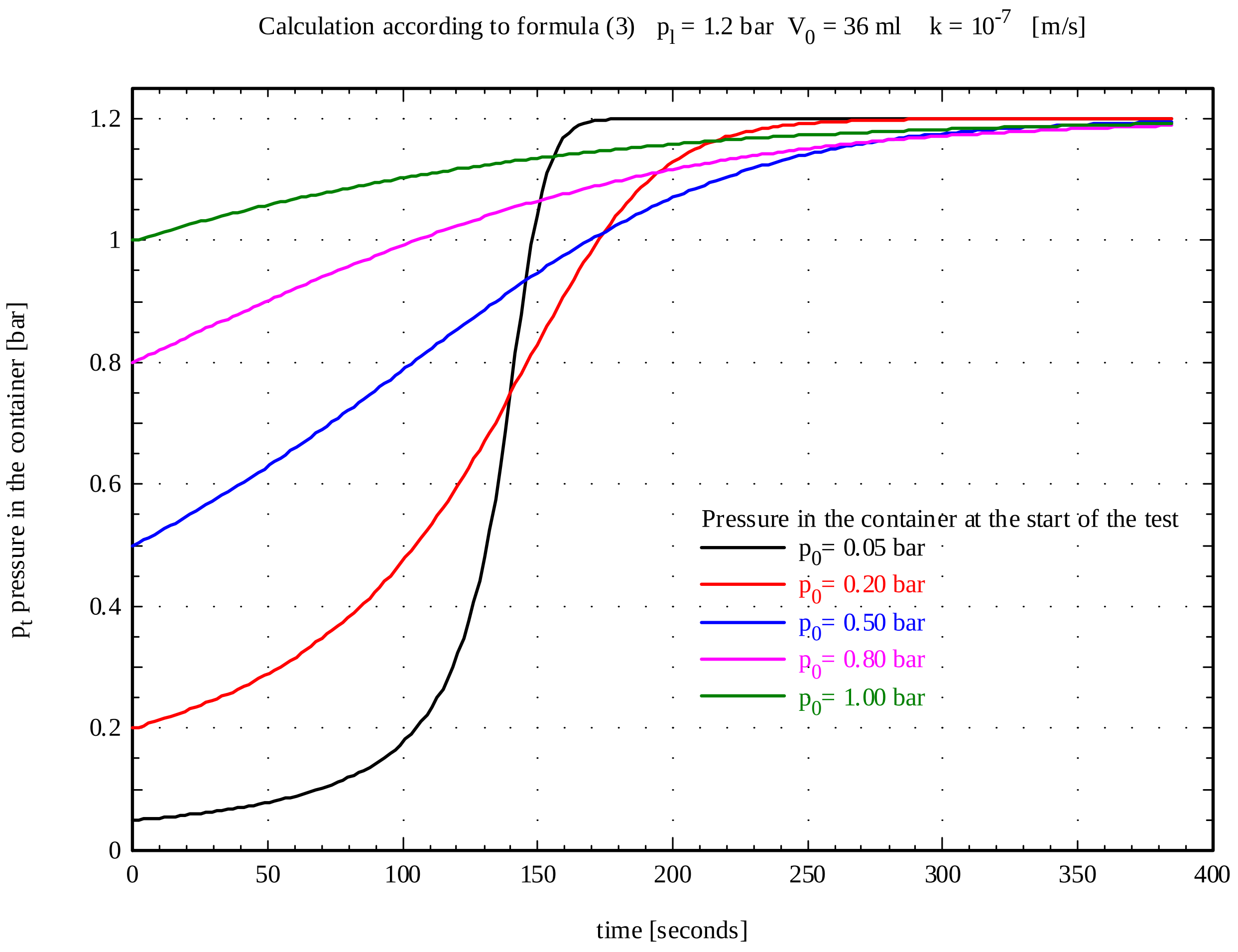
Field Instrumentation in Geotechnical Engineering, T.H. Hanna, *Trans Tech Publications*, Germany, ISBN 0-87849-054-X

Torstensson, Bengt-Arne. 1984. "A new system for groundwater monitoring". *Ground Water Monitoring Review*, v.4, no. 4, pp. 1331-138

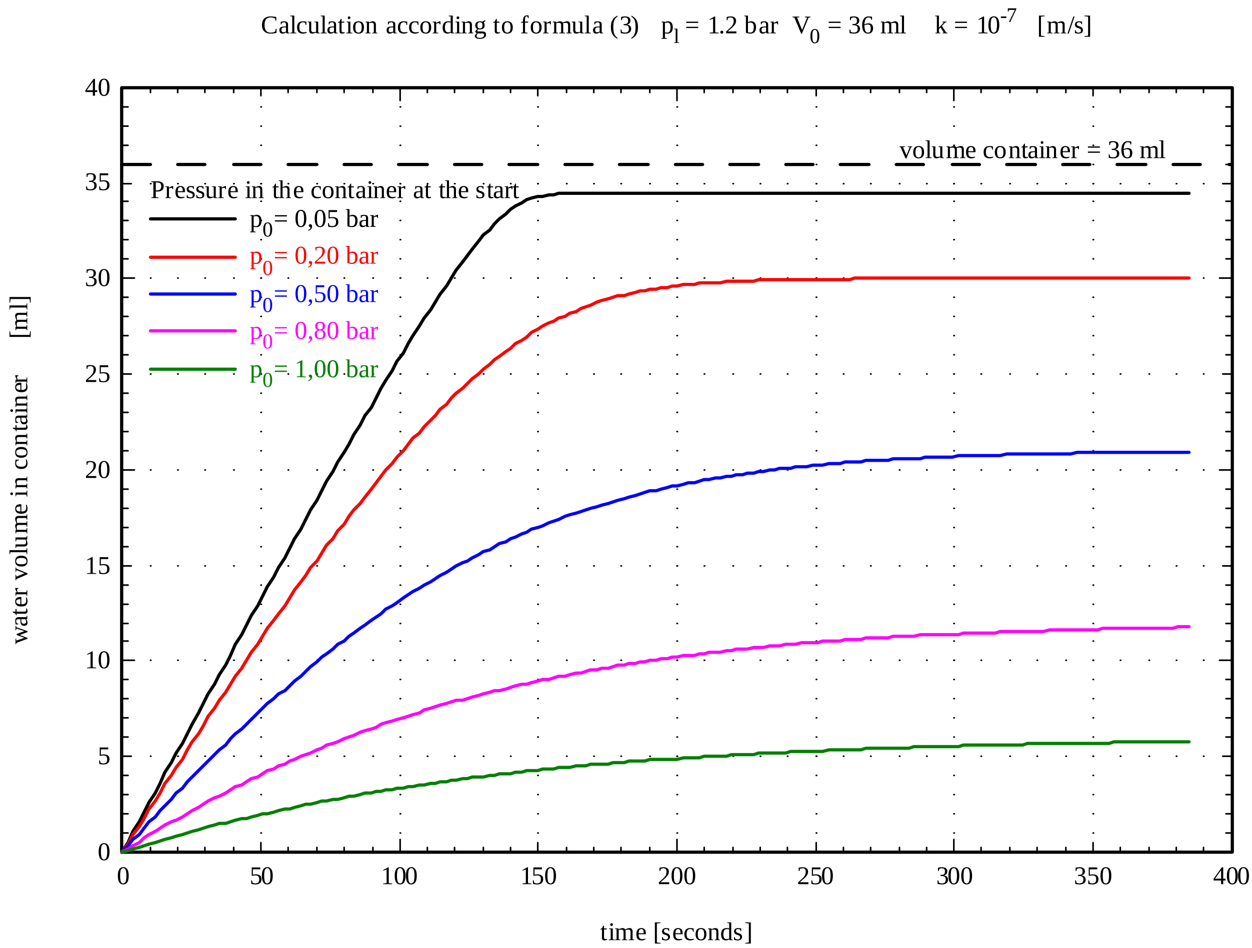
FIGURES:



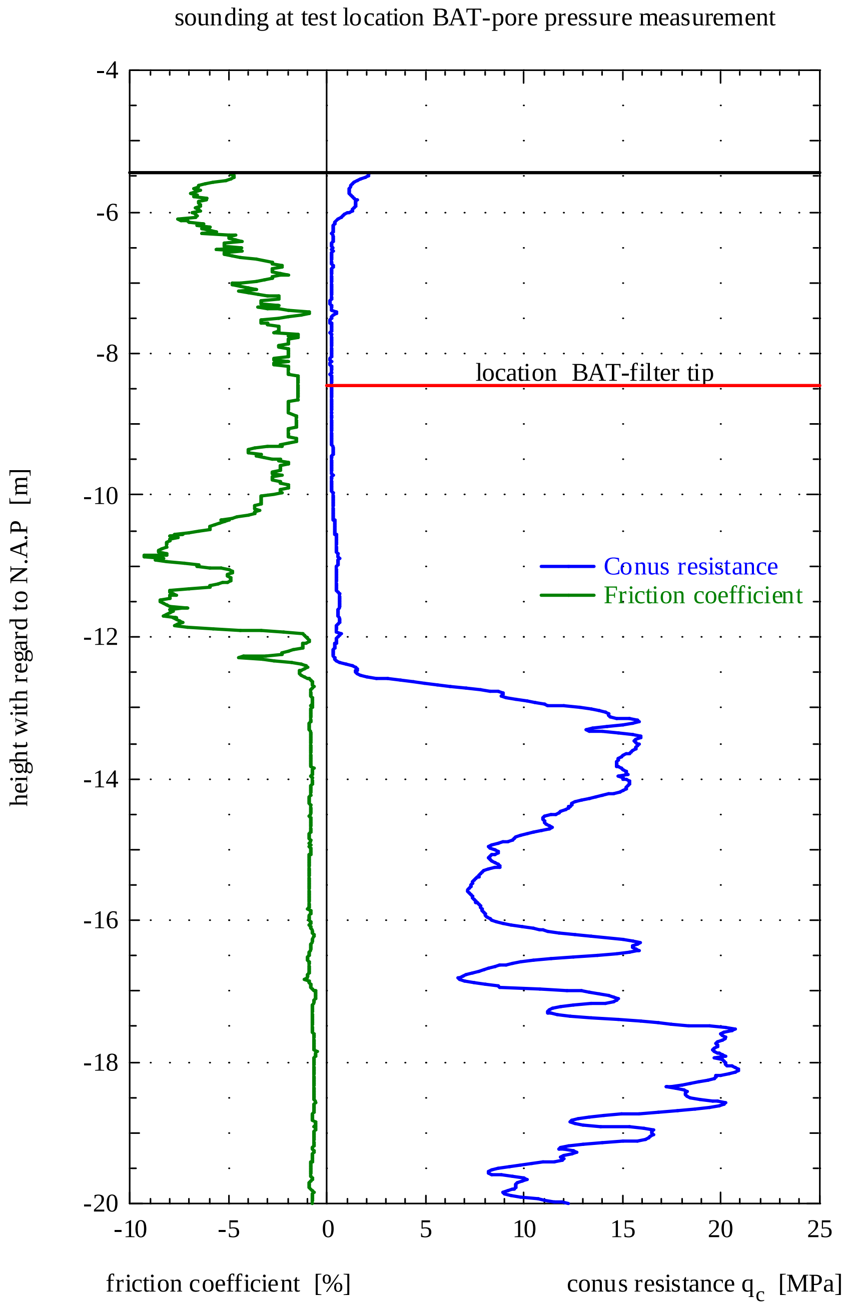
1 Graph with the measured absolute pore pressure at different time intervals. Dissipation of the pore pressure is clearly visible after applying the correction of the air pressure. The abrupt increase on day 14 and 15 is caused by the placement of an extra load.



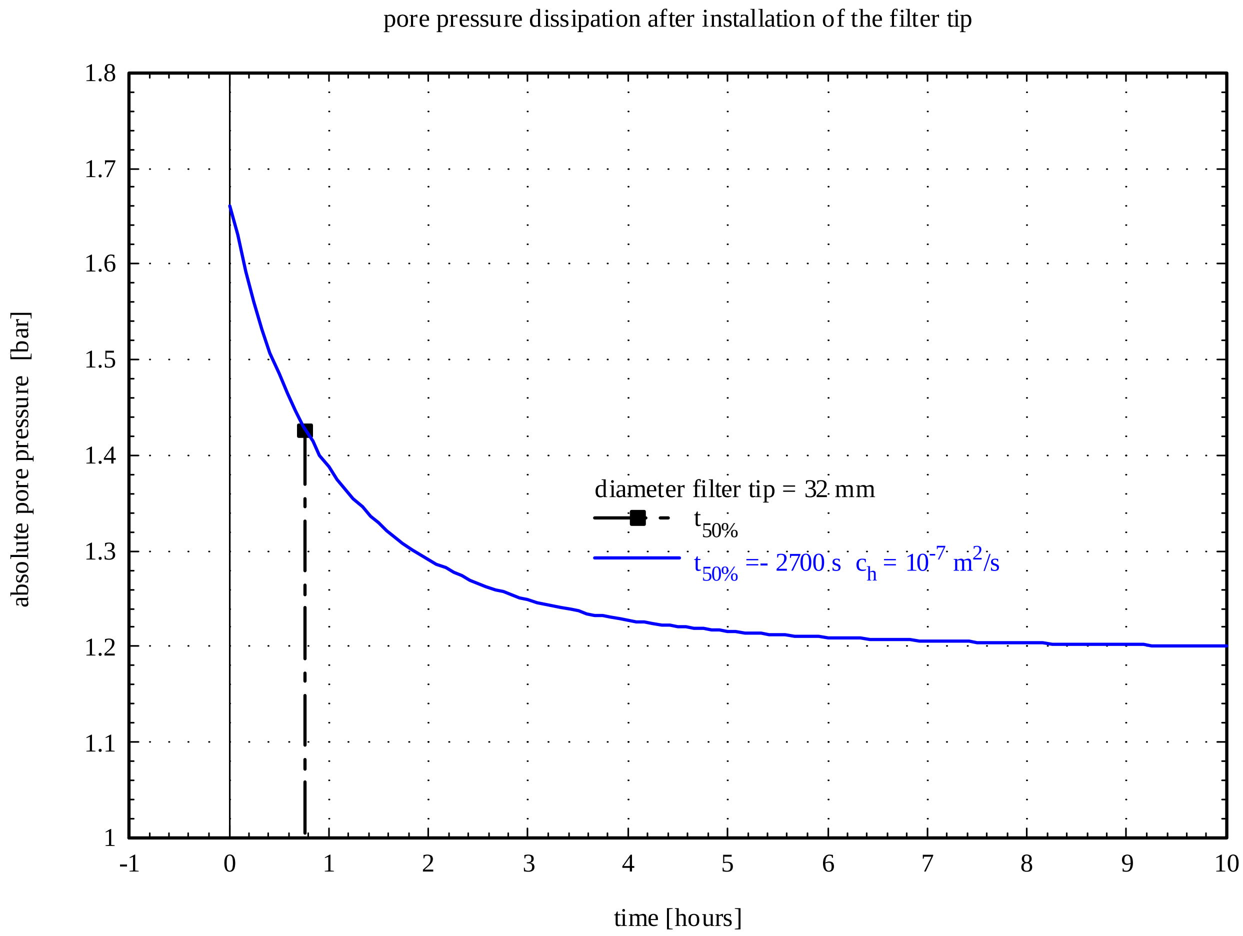
2a Pressure as function of time according to formula 3. The initial pressure in the container varies. The flow factor and the volume of the container are 0.23 m and 36 ml. This parameter choice is based on the BAT®-system.



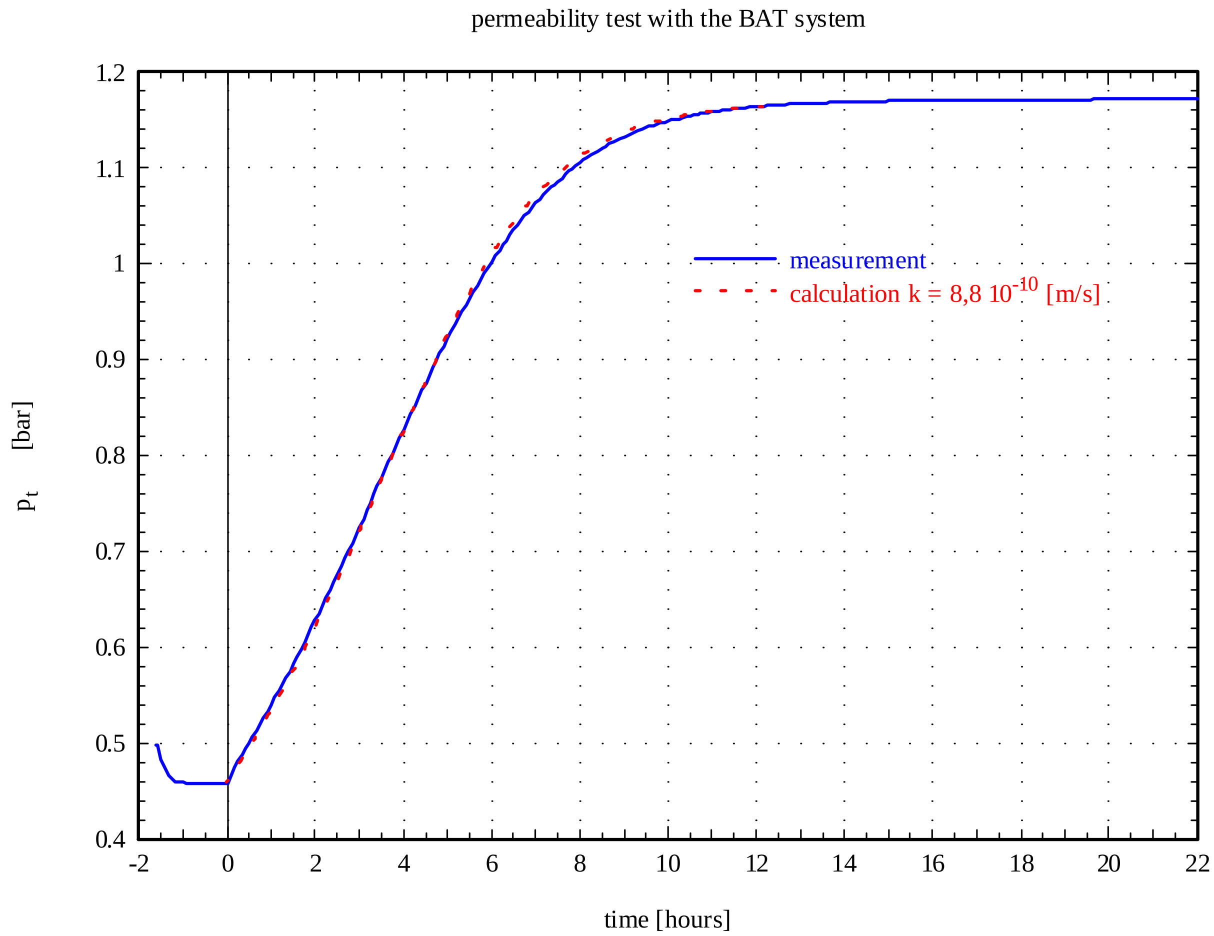
2b Water volume inflow before the pressure-time measurements from figure 2a.



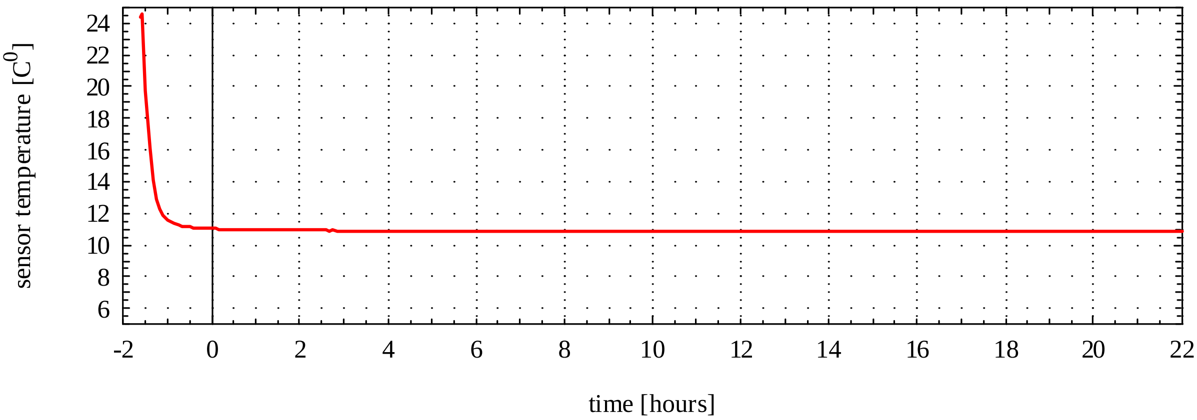
3 Sounding survey at the test location. The filter tip is placed at -8,5m relative to the Dutch reference level: N.A.P. The sounding report mentions: CLAY, moderately silt, mildly humus with sand layers and some shell parts. The following measurements are done with the BAT®-system: a consolidation test, a permeability measurement and a hydraulic fracturing test.



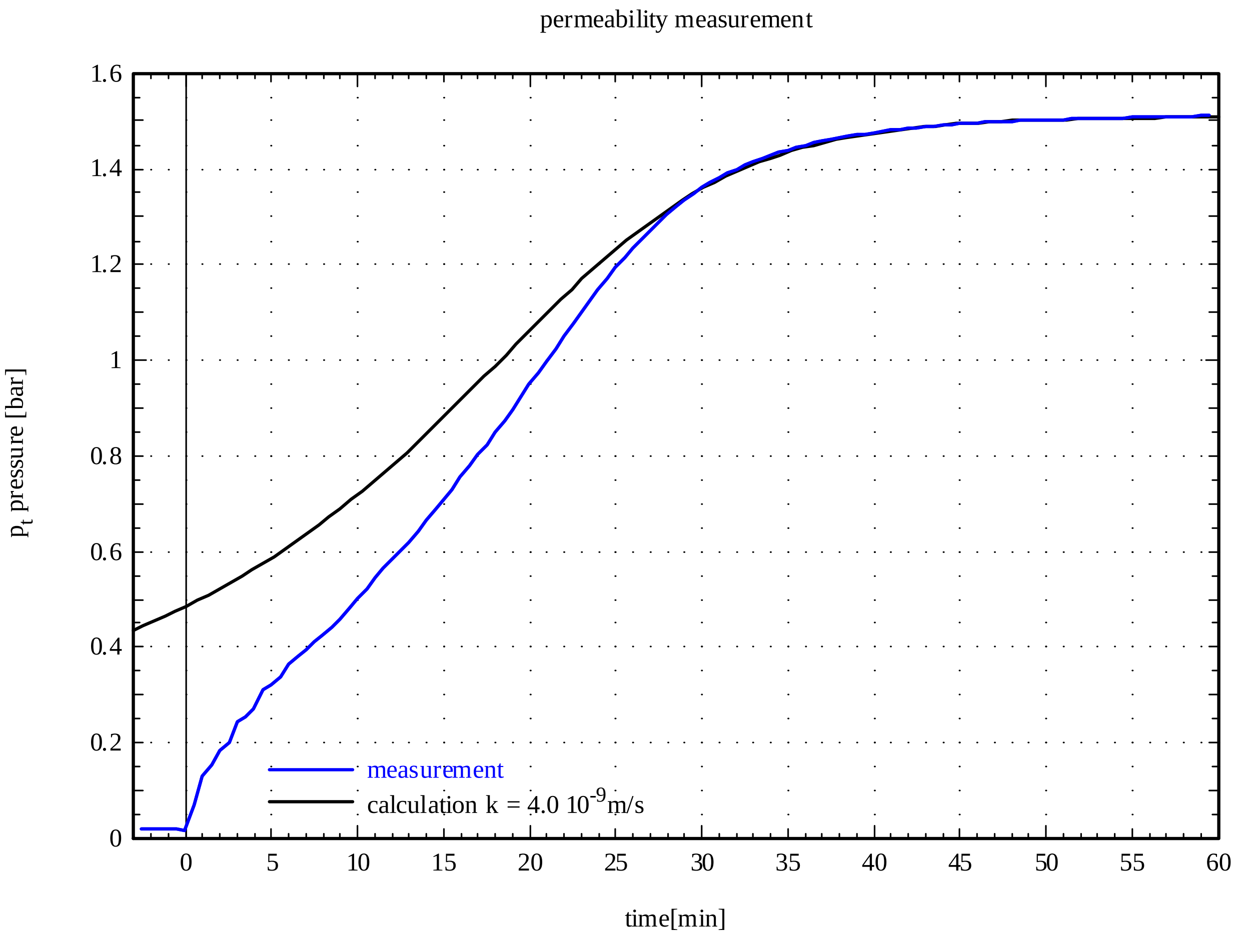
4 Dissipation of the pore pressure after installation of the filter tip. The half-time is about 2700 s. The according to formula 2 calculated consolidation coefficient c_h is in that case 10^{-7} m^2/s. Figure 3 gives the sounding survey at the test location.



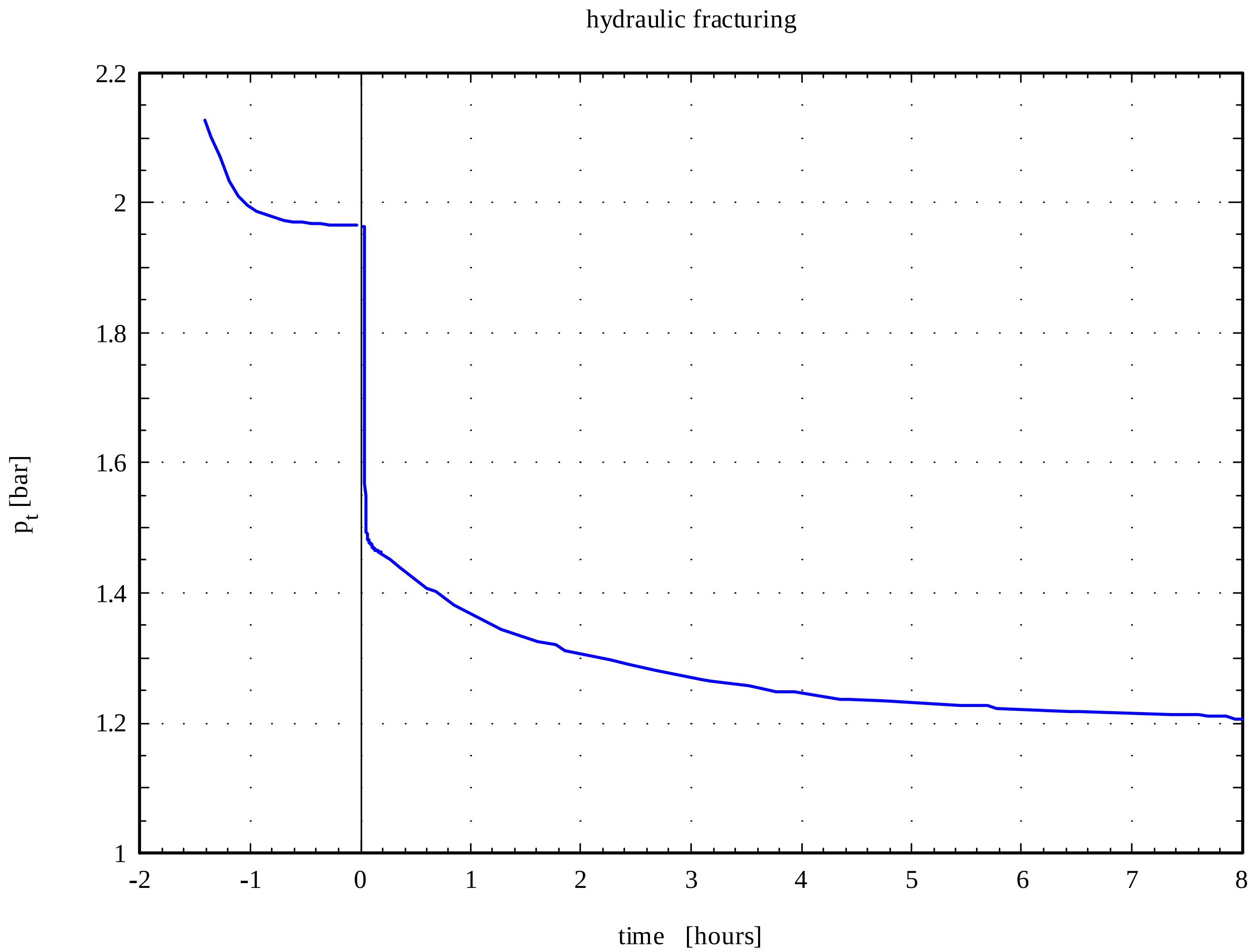
5a Permeability measurement with the BAT®-system. In the graph the calculated curve according to formula 2 is also given. The *k* is 8,8 10^{-10} m/s. The decrease of the pressure in the container before the start of the test is caused by the cooling of the gas in the container. Figure 3 gives the sounding survey at the test location..



5b The sensor temperature at different time intervals during the permeability measurement in figure 5a. The temperature difference between the ground level and the measurement location causes a pressure decrease in the container. The sensor can only then be coupled to the filter tip when the temperature of the gas has been stabilised at the local environmental temperature.



6 Permeability measurement in strongly gaseous soil. The pressure in the container at the start of the test amounts to 25 mbar. At the end of the test the container contains 15% gas with a pressure of 1,52 bar instead of 1,5%. The calculation according to formula 2 is then not applicable anymore.



7 Hydraulic fracturing test. The crossing of both the asymptotes is at 1,48 bar. During the quick decrease of the pressure the pore pressure is larger than the effective stress. Figure 3 gives the sounding survey at the test location.