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A New System for Ground Water Monitoring

by Bengt-Arne Torstensson

Abstract

This paper describes a new system for ground water monitoring, "the BAT System," which includes the following functions: (a) sampling of ground water in most types of soils, (b) measurement of pore water pressure, and (c) in situ measurement of hydraulic conductivity. The system can also be used for tracer tests. The system utilizes a permanently installed filter tip attached to a steel or PVC pipe. Installation is normally performed by pushing the tip down to the desired depth. The filter tip can also be buried beneath a landfill. The primary feature of the new system is that the filter tip contains a self-sealing quick coupling unit, which makes it possible to temporarily connect the filter tip to adapters for various functions, e.g. water sampling and for measurement of pore pressure and hydraulic conductivity. The new technique makes sampling of both pressurized water and gas possible. Samples are obtained directly in hermetically sealed, pre-sterilized sample cylinders. Sampling of ground water and measurement of pore pressure can be repeated over a long period of time with undiminished accuracy. This technique is also well-adapted for taking water samples from different strata in a soil profile, in both the saturated and unsaturated zones. Actual installations range from 0.5 to 60m depth.

System Description

General

The new system for ground water monitoring includes the following functions:

- Sampling of ground water (gas and fluid phases)
- Measurement of pore water pressure
- In situ testing of hydraulic conductivity
- Tracer test for monitoring ground water flow.

The system utilizes a filter tip that is permanently installed in the ground. The filter tip is attached to a 1-inch extension pipe made of steel or of plastic.

The different functions listed above operate by way of different test adapters that are lowered down the pipe. The adapters make a tight seal with the filter tip through the aid of a special quick-coupling unit, which comprises a pre-stressed disc of resilient material and a hypodermic needle.

The basic principle of the new system is that one set of test adapters can serve hundreds of permanently installed filter tips.

BAT filter tip

The key element in the new system for ground water monitoring is the BAT filter tip, shown in Figure 1. This tip consists basically of a thermoplastic body and a filter made of porous plastic (polypropylene) or sintered ceramic. The tip is sealed with a pre-stressed disc of resilient material, e.g. synthetic rubber or crude rubber. The rubber disc is mounted in a nozzle and functions as both a seal and an automatic one-way valve. The filter tip is threaded onto a 1-inch

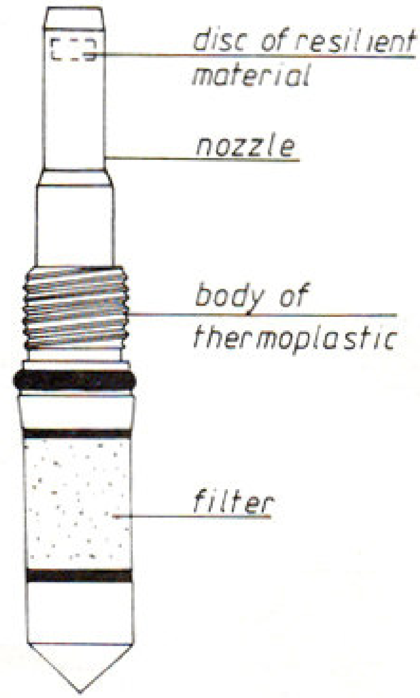

Figure 1. Filter tip

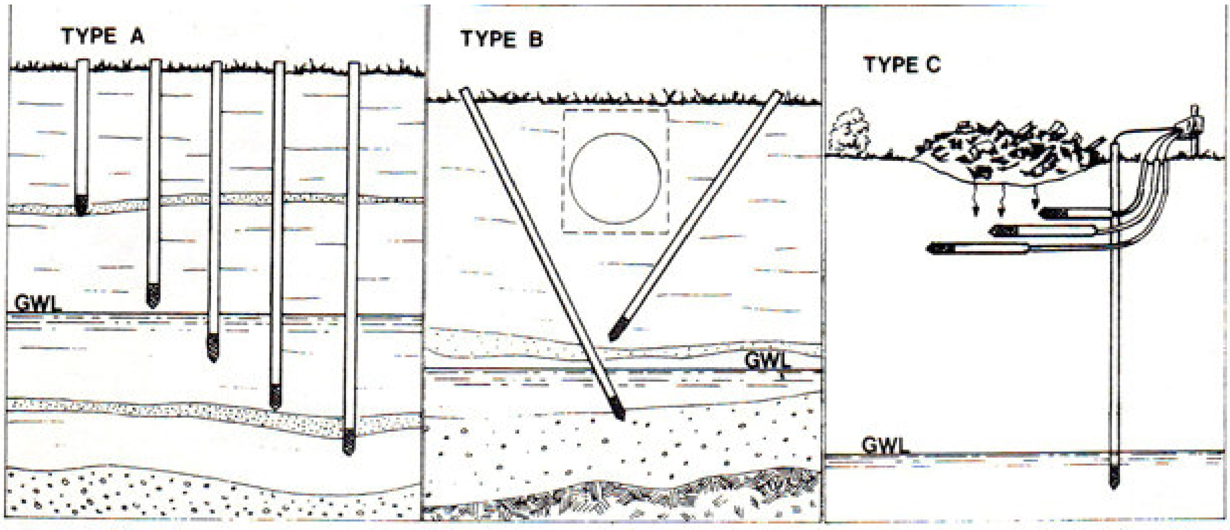

Figure 2. Different modes of installation of the filter tips: a) cluster; b) inclined installation to reach beneath existing underground structures, and c) "horizontal" installation beneath a landfill or a similar structure

extension pipe and is normally installed into the soil simply by pushing it down to the desired level. Figure 2 illustrates different modes of installation of the filter tips. Figure 2a shows a cluster of filter tips installed at different depths for sampling of ground water and measurement of pore pressure in various soil strata. Figure 2b shows an inclined installation in order to reach beneath an underground storage tank etc., whereas Figure 2c shows filter tips that are buried beneath a landfill.

The standard filter tip (Figure 1) is furnished with a reinforcing core of Teflon-coated stainless steel. When installed in fine-grained soils, this filter tip can sustain an installation force of approximately 2 tons. For harder soils special filter tips have been developed, namely one that has a body of stainless steel and another type (heavy duty filter tip), which has a filter molded inside the body of stainless steel or brass. It is also possible to install the filter tips in pre-drilled holes and to seal off the test section with a bentonite slurry.

The different test adapters make a tight, temporary connection to the filter tip with the aid of a hypodermic needle (Figure 3). When the test adapter is lowered down the extension pipe, it is coupled to the nozzle in the filter tip and gravity draws the hypodermic needle downward, penetrating the rubber disc, mounted in the filter tip. The needle provides a hydraulic connection between the interior of the filter tip and the test adapter.

Eight years experience has shown that the rubber disc can be penetrated by the hypodermic needle hundreds of times without loss of its automatic, self-sealing, one-way valve function.

Pore pressure measurement equipment

Figure 4 shows a photo of the test adapter for pore pressure measurements. The test adapter is lowered onto the filter tip for each pore-pressure reading.

The pore pressure adapter contains a hypodermic needle and an electronic pressure transducer, which is connected to a battery-operated digital readout unit via a cable. Between the hypodermic needle and the diaphragm of the pressure transducer is a fluid-filled cavity. The readout unit's display clearly indicates when the needle penetrates the rubber disc in the filter tip. A stable value for the pore pressure is nor-

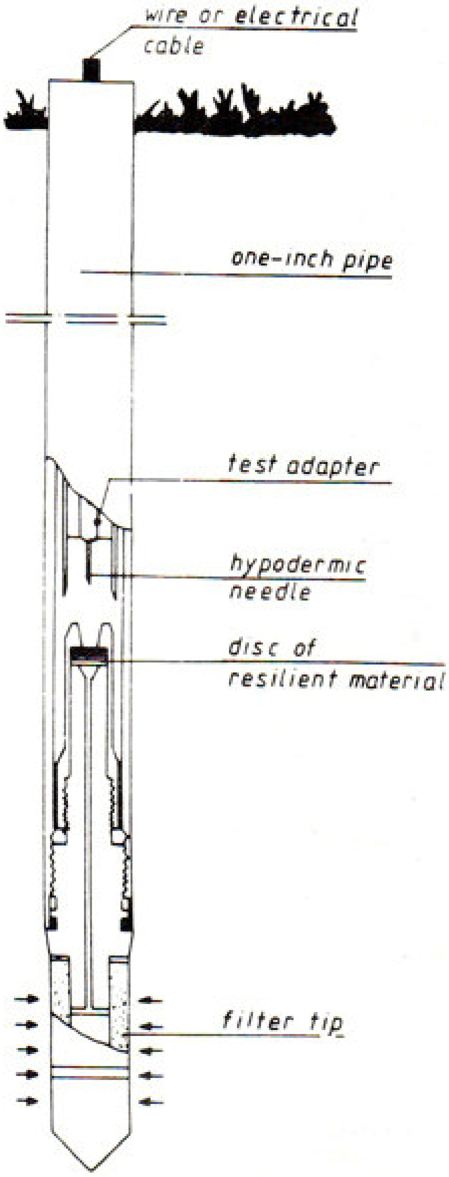

Figure 3. A test adapter is lowered onto the filter tip. The adapter makes a tight, temporary connection to the filter tip with the aid of a hypodermic needle

mally obtained after a few minutes, even in highly plastic clays. The standard pressure range of the pore pressure adapter is from -10 to 150m of water column.

Ground water sampling equipment

Figure 5 shows a schematic diagram of the equipment used for sampling ground water and gas. Samples are obtained in hermetically sealed, pre-sterilized and evacuated glass cylinders. A sample cylinder, sealed with a rubber disc, is mounted in a sampling adapter. The adapter is equipped with a double-sided hypodermic needle, mounted on a track in the adapter nose.

Prior to evacuation, the sample cylinder can be filled with nitrogen in order to increase the chemical inertness of the system. The interior of the cylinder can be coated with Teflon if required.

The glass containers can be used to a maximum pressure of 200m of water column. For high-pressure applications, containers of stainless steel must be used.

The standard sampling equipment is designed for 1-inch extension pipes. This version can hold sample containers with a volume of 35ml (Figure 6). By using extension pipes with a greater diameter than 1 inch, e.g. 1.5- or 2-inch diameter, the sample volume can be increased to 200-500ml.

Samples of ground water and/or gas are taken by lowering the adapter down the extension pipe. When the adapter connects to the nozzle of the filter tip the double-sided hypodermic needle will penetrate both the rubber disc in the nozzle and the rubber disc in the sample cylinder. This provides a connection between the sample cylinder and the interior of the filter tip. Due to the underpressure in the sample cylinder, ground water (e.g. pore water) will be sucked into the container via the filter tip.

The penetration of the double-sided hypodermic needle through the rubber discs is aided by use of a chain of weights attached to the sampling adapter.

Some special features of the new ground water and gas sampler include:

- samples of ground water and gas can be obtained with a high degree of cleanliness: no air contact and no external contamination
- samples can be obtained with constant quality—independent of the skillfulness of the person taking the sample
- volatile constituents (e.g. organic solvents) can be accurately sampled
- samples of ground water can be collected from almost all types of soils, including impervious clay
- sampling can be carried out with undiminished accuracy at great depths
- samples can be easily collected, even when freezing temperatures occur on the ground surface
- the sampling technique minimizes risks that the operator comes into contact with dangerous chemicals, etc.

It should also be noted that the new technique enables sampling of pressurized water. If the sample adapter remains connected to the filter tip the pressure in the sample container will finally equalize the pore water pressure in the soil. The time needed for pressure equalization is a function of the hydraulic conductivity of the soil. When it is disconnected from the filter tip the sample adapter closes automatically, i.e. the pressure in the sample cylinder is preserved as the water and/or gas sample is taken to the laboratory.

Figure 4. Test adapter for pore pressure measurement being inserted into the one-inch extension pipe

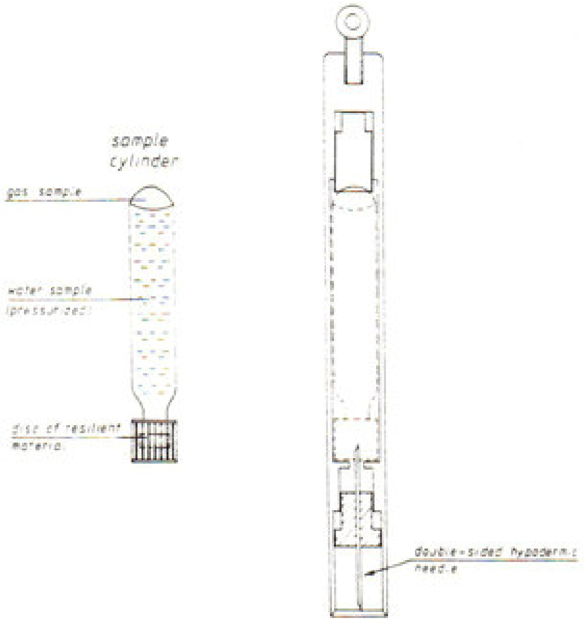

Figure 5. Schematic of test adapter for sampling of ground water and gas

The ability to sample pressurized water is greatly important in the analysis of dissolved gases in water.

Results from pore water sampling

In 1981, a test series using the new ground water monitoring system was initiated at the Verka basin, 35km north of Stockholm.

At the Verka site, the installation of the BAT System represents only a small part of a larger project with basic aims of: (a) making a detailed study of the circulation of salts in the soil layers, and (b) monitoring both the movement and the recharge of ground water (Nilsson and Armolik 1980).

The soil profile at the Verka test location consists of a very soft clay to a depth of about 16m. The clay is very homogeneous to a depth of about 12m. In the depth interval of 12-16m the clay is slightly varved.

Filter tips were installed at three test locations. At one site four filter tips were installed at the depths of 9, 12, 14 and 16m (Figures 7 and 8). All filter tips were installed in a very soft, impervious clay. The filter tip at 16m depth was, however, situated close to a more pervious bottom soil layer. The purpose of this installation was: (a) to obtain information about the variation of pore water chemistry with depth by in situ water sampling, and (b) to monitor, by repeated sampling, the variation of pore water chemistry with time at certain installation depths. Since the filter tips were installed in a thick layer of impervious clay, in which it was not likely that the pore water chemistry would vary with time, it was expected that the test series would provide information about the repeatability of the sampling technique. At 16m installation depth, however, seasonal fluctuation of the water chemistry might occur due to influence from the more pervious bottom soil layer.

Pore pressure measurements were carried out concurrent with sampling of pore water. Conductivity tests were also conducted (Figure 12). The results from these tests show that the clay has a coefficient of hydraulic conductivity on the order of 1.5×10^{-10} m/s at all four test elevations.

Figure 7 shows a depth profile of Cl^- concentration at the Verka test location. Sampling of pore water was carried out at 1m-depth intervals. These samples were taken during the installation process of the four permanent filter tips. As shown in Figure 7 the Cl^- concentration in the pore water increases nearly linearly with depth from a value of 15 meq/L at 2 m depth

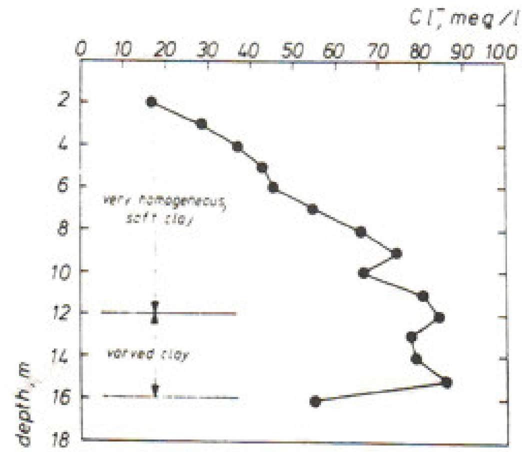

Figure 7. Cl⁻ —profile at the Verka test site

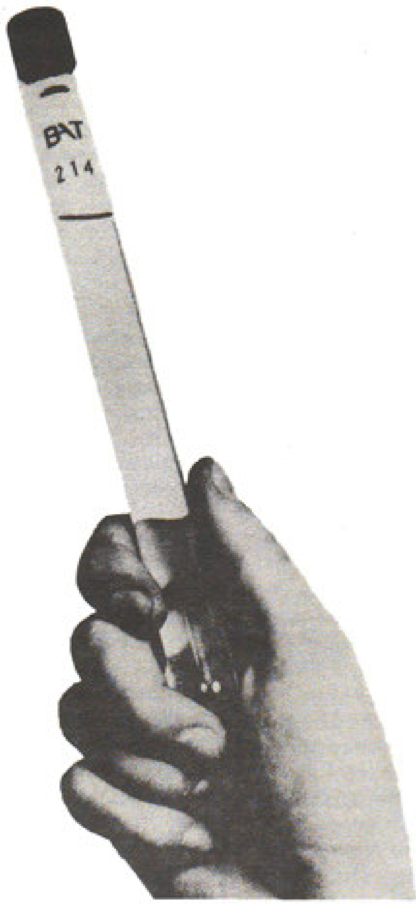

Figure 6. The standard sample container has a volume of 35 ml

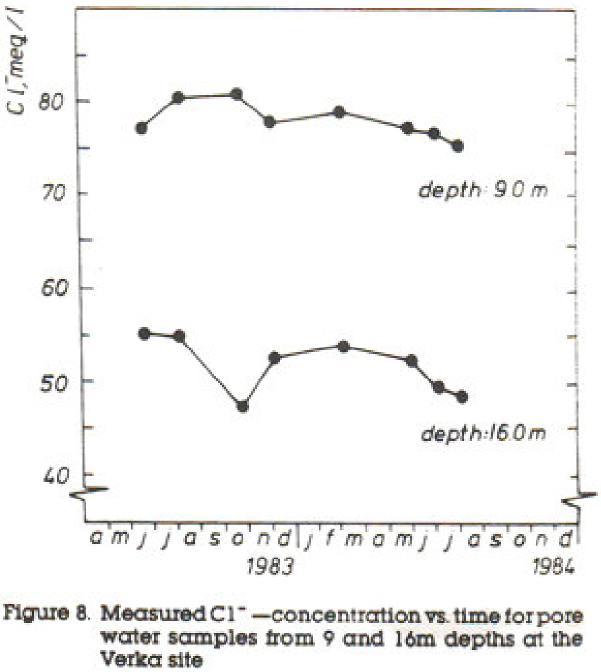

Figure 8. Measured Cl⁻ —concentration vs. time for pore water samples from 9 and 16m depths at the Verka site

to 85 meq/L at 12m depth. In the depth interval of 12-15m the Cl^- concentration remains fairly constant with an average value of 85 meq/L. At a depth of 16m the Cl^- concentration is reduced to 55 meq/L, indicating an influence on the pore water chemistry from the more pervious bottom soil layer.

The study at the Verka basin has demonstrated that the sampled pore water from the central section clay layer originated from the prehistoric sea in which the clay was deposited some 7,000 years ago.

Figure 8 summarizes the results of repeated pore water sampling at the depths of 9 and 16m. Sampling was performed during a 14-month period. The sampling interval averaged two months.

Figure 8 shows measured Cl^- concentrations vs. time. At a sampling depth of 9m the Cl^- concentration averaged 78 meq/L during the sampling period. As mentioned above, it is unlikely that the pore water chemistry will vary with time at this sampling depth. The maximum measured variation in Cl^- concentration was only 3 meq/L, i.e. about 4 percent of the average value. This result indicates that the sampling technique has an acceptable degree of repeatability.

At 16m sampling depth the Cl^- concentration averaged 52 meq/L. The maximum measured variation in Cl^- concentration was 8 meq/L, i.e. about 15 percent of the average value. This variation is probably due to seasonal fluctuations of the ground water chemistry in the pervious bottom soil layer.

System for in situ measurement of hydraulic conductivity

The system arrangement for in situ measurement of hydraulic conductivity is shown in Figure 9. The measuring system comprises a test adapter that is equipped with a double-sided hypodermic needle and a gas/water container. The pressure in the container is measured with the aid of an electronic pressure transducer.

The test can be carried out either as an "inflow test" or as an "outflow test." In the former case the gas/water container is completely gas-filled at the start of the test. An inflow test can be conducted simultaneously with the extraction of a pore water sample. In an outflow test the container is partly filled with water and partly filled with compressed gas.

The test arrangement for an outflow test can also be used for the controlled injection of a tracer liquid into the soil. The spreading of this liquid can be checked by repeated sampling in filter tips installed at different distances from the point of injection.

It should be noted that the test provides information mainly about the hydraulic conductivity in the horizontal direction. Due to natural stratifications, the horizontal conductivity is often many times greater than the conductivity in the vertical direction.

Test procedures and evaluation of test data

The initial pressure in the gas/water container and the equilibrium pore pressure in the soil is denoted p_0 and p_1, respectively. Before the start of the test the pore pressure p_1 is measured in a conventional manner. The initial pressure p_0, which can be chosen arbitrarily, is easily applied, e.g. with the aid of either a syringe or a pressure regulation valve and a gas bottle.

After preparation, the test adapter is lowered down the extension pipe. Temperature equalization is achieved before connecting the adapter to the filter tip. When the adapter is lowered on the nozzle in the filter tip it is automatically connected to the tip with the aid of the double-sided hypodermic needle. Upon connection of the test adapter to the filter tip the pressure in the gas/water container starts to change. The change in pressure is recorded using the same electronic pressure transducer, mentioned above. Figure 10 shows a typical pressure equalization curve for an inflow test.

The pressure change in the test adapter is quite similar to a falling-head test in a standpipe and can be analyzed by the falling-head theory as defined by Hvorslev (1951). According to Hvorslev the following flow equation applies:

$$q = Fk\,(p_1 - p_0) \tag{1}$$

in which

q = fluid flow (m^3/s)
F = flow factor (m)
k = coefficient of hydraulic conductivity (m/s)
p_1 = equilibrium pore pressure (m H_2O)
p_0 = initial pressure in test adapater (m H_2O)

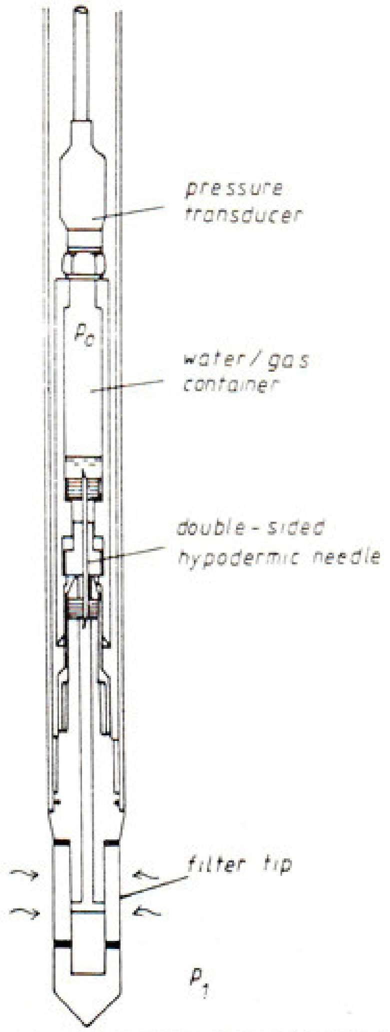

Figure 9. Schematic of the system for in situ measurement of hydraulic conductivity

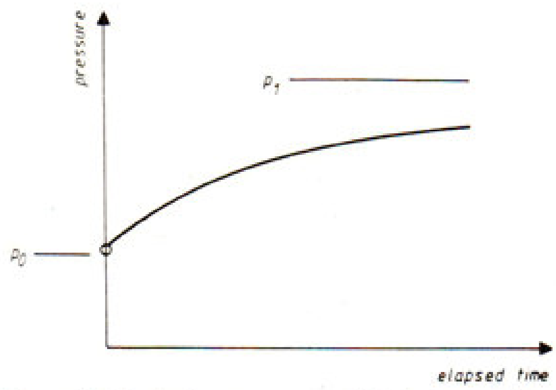

Figure 10. Typical pressure equalization curve for an inflow conductivity test

Hvorslev (1951) further defines the flow factor $\bar{F}$ as follows:

$$F = \frac{2\pi l}{\ln\left[l/d+\sqrt{1+(l/d)^2}\right]} \quad (2)$$

in which

l = length of filter (m)
d = diameter of filter (m)

The condition of continuity requires:

dV = -qdt

in which

dV = volume change (m) during time interval dt (s) (3)

The pressure/volume relationship of the gas-filled test container can be defined by Boyle's-Mariotte's law:

$$P_0V_0 = pV \quad (4)$$

in which

V_0 = initial volume (m^3) in test container
V = volume in test container at time t
p = pressure (absolute)

Boyle's-Mariotte's law is valid for constant temperature. This requirement is normally met for the actual conditions of testing.

By combining Equations 1, 3 and 4 the following expression for the coefficient of hydraulic conductivity k from an inflow test can be derived (Bengtsson 1984):

$$k = \frac{P_0V_0}{Ft}\left(\frac{1}{p_1p_0} - \frac{1}{p_1p_t} + \frac{1}{\frac{2}{p_1}}\left(\ln\frac{p_0-p_1}{p_0}\cdot\frac{p_t}{p_t-p_1}\right)\right) \quad (5)$$

in which

p_t = pressure in test adapter at time t

(All pressures p in Equation 5 are express in absolute pressures).

The new system can be used for testing in soils, having a coefficient of hydraulic conductivity that is less than 1×10^{-6} m/s. The limiting factor is the flow capacity of the hypodermic needle. Figure 11 shows the flow characteristics of the hypodermic needle used in the system.

The BAT apparatus can take several different gas-water containers of differing volume V_0, allowing a wide range of dp/dV values. This permits tests to be carried out with no loss of accuracy even at very low hydraulic gradients. Another important feature of the new system is that conductivity tests can be conducted with constant precision, independent of testing depth.

Comprehensive investigations made by Petsonk (1984) have shown that the system yields surprisingly accurate and consistent values for soil conductivity in a variety of situations.

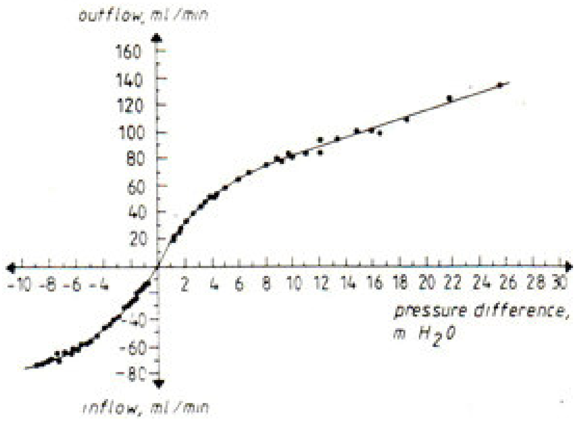

Figure 11. Flow characteristics of the hypodermic needle, used in the system for measurement of hydraulic conductivity

Test results

Figure 12 illustrates a plot of test data for an inflow conductivity test. The actual installation is made in a very soft clay at a depth of 9m below ground surface. The test location is the Verka River basin (Figures 7 and 8).

The test results are plotted in the form of a pressure equalization diagram, i.e. pressure ratio $\ln((p_1-p_0/p_1-p_t))$ vs. time. For the actual test the following initial conditions apply:

- Static pore pressure p_1=8.32 m H_2O
- Initial pressure p_0=-2.51 m H_2O
- Volume of gas in container V_0=121.5ml.

In order to study the consistency of the values of the coefficient of hydraulic conductivity as calculated for different testing times, the actual test was run for a period of 2.5 days. Table 1 summarizes values calculated during this test.

Table 1

Calculated values of coefficient of hydraulic conductivity k for different testing times.

Testing time (min)	202	502	1,002	2,002	3,702
Coefficient of hydraulic conductivity $k \times 10^{-10}$ (m/s)	1.53	1.59	1.48	1.49	1.39

Average k value: 1.45×10^{-10} m/s

It can be seen that the calculated values of the coefficient of hydraulic conductivity show only a small variation with length of testing time. The test results suggest that the new system enables tests to be conducted in soils of very low conductivity by using a testing time of only a couple of hours. In soils having a coefficient of hydraulic conductivity within the range of 10^{-6} to 10^{-8} m/s the test can be conducted in only a few minutes.

Figure 12 shows, for sake of comparison, the theoretical pressure equalization curves corresponding to k values of 1.4×10^{-10} and 1.6×10^{-10} m/s, respectively.

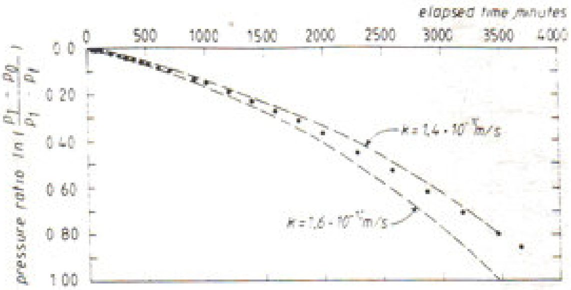

Figure 12. Test data for a longterm in situ test of hydraulic conductivity. Test location: Verka, depth of testing 9.0m

It may be noted, that upon completion of a test of soil conductivity, the results may be controlled by measuring the volume of water that has entered into or flowed out of the gas/water container. Ideally, this volume should correspond to the theoretical volume change as calculated from Equation 4.

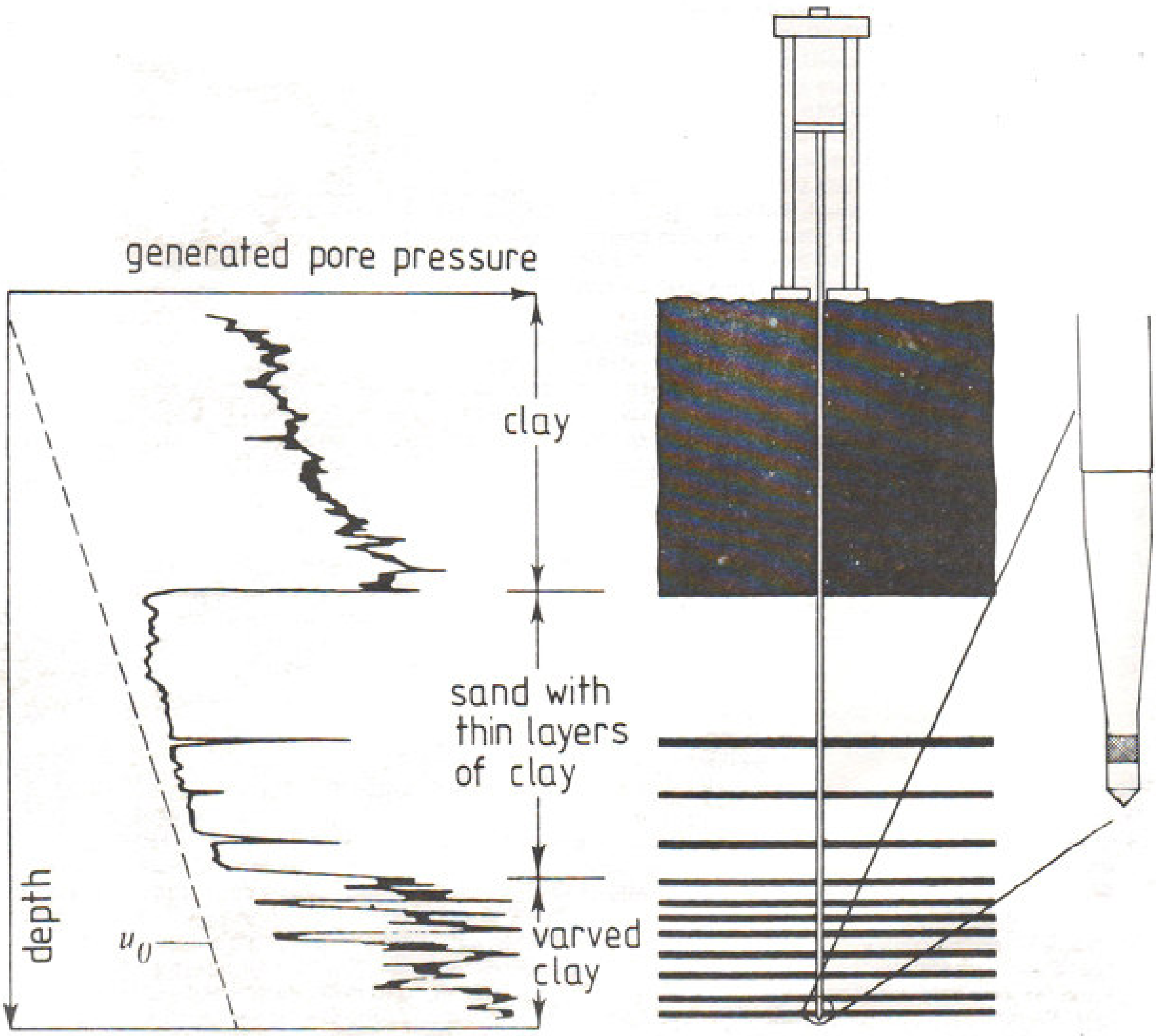

Figure 13. Typical pore pressure sounding diagram for a layered soil. (u_0=equilibrium pore pressure)

Installation of Filter Tips

Finally, it is appropriate to discuss installation techniques for filter tips. When filter tips are installed for the purpose of ground water monitoring it is important to consider the stratification of the actual deposit. For example, if the soil profile contains permeable layers embedded in impermeable soil, these layers may be critical for the spread of pollutants in the ground water.

The pore pressure probe, (Torstensson 1975 and 1977), is a tool that provides detailed information about the stratification of soft, saturated soils. It is especially suited for the indentification of permeable layers in cohesive soil. This system utilizes the pore pressures that are generated when a conical filter tip penetrates the soil at a constant speed (Figure 13). The generated pore pressure is primarily a function of the hydraulic conductivity of the soil layers. In normally consolidated clays, high excess pore pressures are generated. In more permeable soils, such as sand and silt, penetration of the pore pressure probe normally generates only small excess pore pressures. The probe has an extremely rapid response to changes in pore water pressure. Thus, embedded seams of sand or silt in clay are distinctly shown as sudden pressure drops on the pore pressure/depth diagram. On the other hand, thin clay layers embedded in sand are shown as sudden pressure peaks. Figure 13 shows an idealized pore pressure sounding diagram for a layered soil.

Compared with the traditional method of measuring the cone penetration resistance, the pore-pressure probe is a much more sensitive tool for registration of the stratification of a saturated, soft soil deposit.

Prior to the installation of permanent filter tips for ground water monitoring, the pore pressure probe can provide useful information for the selection of relevant installation depths.

The permanent filter tip is normally installed by pushing it down to the desired depth. During installation it is very useful to utilize the filter tip itself as a pore-pressure probe. Using this procedure it is possible to install the filter tip exactly in a pre-selected soil layer. By choosing a suitable filter height, the filter tip can, for example, be installed in embedded permeable layers with a thickness of not more than 5-10mm.

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Biographical Sketch

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