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STATENS GEOTEKNISKA INSTITUT
SWEDISH GEOTECHNICAL INSTITUTE

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No 37

Pore Pressure Measurement – Reliability of Different Systems

Marius Tremblay

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AB ÖSTGÖTATRYCK LKPG

PREFACE

This report presents an evaluation of different systems used for pore pressure measurement. The investigation deals with the behaviour of these systems when used for measuring natural variations in the groundwater conditions. The influence on the measurements of changes in the atmospheric pressure is also studied, as well as the various problems occurring with measuring instruments used for automatic reading and recording of the pore pressure in a slope stability monitoring system. The results presented here are therefore of interest for anyone concerned with the choice of a system for long-term measurement of pore pressure.

The evaluation of the different systems is based on measurements performed on a number of sites located in Sweden. The majority of the results presented here were obtained from a research project carried out in 1984-85 during the author's stay as a guest-researcher at the Swedish Geotechnical Institute (SGI). Some additional measurements found in this report are taken from different projects previously conducted at SGI.

The author would like to express his sincere thanks to Dr. Jan Hartlén, Director General of SGI, for making this stay possible and also for his constant interest and encouragement.

The author is especially indebted to Mr. Ulf Bergdahl, the supervisor of this research project, for his constant support and encouragement during this work. His comments during the field work and the discussion of the results were highly appreciated.

Special thanks are expressed to Mr. Sören Eskilsson, for his valuable comments regarding the evaluation of the various measuring systems and the interpretation of the results, and also for giving the author the opportunity to use measurements from Örebro and Skå-Edeby. The author also wishes to thank Mr. Jan Wennerstrand, formerly of SGI, for his help in the first steps of this research project, and Mr. Olov Lindholm, for his assistance during the period of measurement.

Finally, the author wishes to express his gratitude to the staff of SGI for their support, especially to the field engineers for their help in installing the instruments, and the information department for their assistance during the preparation of this report.

Linköping, September 1989

Marius Tremblay

CONTENTS

SUMMARY

This report presents the results of investigations performed at the Swedish Geotechnical Institute (SGI) regarding different systems used for measuring pore pressure. The purposes of the investigation were:

- to study the behaviour of different systems when measuring natural variations in the groundwater conditions;
- to study the influence of changes in atmospheric pressure on the measurements;
- to determine the essential characteristics of a measuring system (piezometer and recording instrument) required for reliable long-term measurement of pore pressure.

The first part of the report includes a presentation and a short evaluation of the measuring systems most commonly used in Sweden. The advantages and disadvantages of these systems are presented, and their applications and shortcomings are briefly discussed.

Measurements performed at Örebro and Linköping show that measuring systems based on different principles may be used for following natural variations in the groundwater conditions in clayey soils. The investigation shows that even open systems can be used for this purpose.

The study of the behaviour of relative pressure transducers performed at Skå-Edeby indicates clearly that severe problems may occur if the device used for the transmission of the atmospheric pressure to the transducer becomes defective. In such a case, variations in the air pressure may affect the pore pressure measurement and make the interpretation difficult.

In order to understand and clarify the phenomena observed at Skå-Edeby regarding the influence of the atmospheric pressure, an analysis of this problem was also made at Linköping. Pore pressure measurements performed with absolute pressure transducers were compared with the values obtained from relative pressure transducers. This investigation shows that changes in atmospheric pressure affect directly the pore pressure measurements performed with absolute pressure transducers. Therefore, these variations must be taken into account in the interpretation.

After the observations made at Linköping and Skå-Edeby, it was concluded that it is preferable to use absolute pressure transducers and to correct the pore pressure measurements for the variations in atmospheric pressure observed on the site.

Finally, a pore pressure measuring system was chosen and installed in a slope in the municipality of Munkedal. The system comprises BAT filter tips and electrical transducers fabricated at SGI. It was integrated in a slope stability monitoring system tested on this site. Pore pressure measurements were performed on a continuous basis for more than 18 months using an automatic reading and recording system. The results pointed out the various problems related to long-term measurement of pore pressure.

The most valuable operational characteristic of the system is the possibility to remove the electrical transducer from the filter tip, which permits the following operations to be performed:

- control of the measurements with a manual reading device;
- calibration of the transducers whenever necessary;
- replacement of defective transducers.

The experience acquired during this period confirmed the suitability of the system chosen for these measurements, its flexibility being one of the most important characteristics.

1. INTRODUCTION

This investigation is the first step of a program undertaken at the Swedish Geotechnical Institute to develop a slope stability monitoring system in which the pore pressure is one of the essential parameters. The purpose of the investigation is to study different systems used for measuring pore pressures in order to find the type of instrumentation most appropriate for such a monitoring system.

The analysis of slope stability is one of the geotechnical problems where groundwater conditions are of great importance. In such analysis, the water flow distribution in the slope and its vicinity, as well as the pore pressure variations in the various layers, have to be analysed.

Despite the fact that the soil behaviour is greatly affected by the groundwater conditions, very often the only information available to the geotechnical engineer is the groundwater level under which he has to assume a hydrostatic distribution of the pore pressure. This information is insufficient for a proper consideration of the problems due to groundwater, especially in clay deposits where the pore water pressure distribution is not controlled by the level of the water table but may be affected by several different factors.

The first part of this report is a short literature survey followed by a presentation of different methods for pore pressure measurement After a re-interpretation of the results from a number of projects conducted at the Swedish Geotechnical Institute, the study of different measuring system is presented. Finally, the report includes the presentation and analysis of pore pressure measurements performed with a slope monitoring installation.

2. LITERATURE SURVEY

2.1 INSTRUMENTS AND MEASURING SYSTEMS

A large number of papers, reports and books dealing with pore pressure measurement can be found in the literature. Most of these papers deal with measurements under dams, large embankments or buildings. They usually include a description of the installation and a presentation of the results obtained from the measurements but seldom provide information about the instruments installed. These papers are therefore of limited interest for the present study.

The contribution of the pore pressure in the evaluation of effective stresses in soil, saturated or unsaturated, is explained in Hannah (1975) and Hult (1984). These two publications include a description of the basic principle of the measurement of pore pressure and a presentation of a number of instruments and measuring systems. An explanation of the problems occurring during the installation or the period of observation can also be found in these two publications. A more elaborate and complete description of different systems available for pore pressure measurement is given by Dunnicliff (1981, 1988), Bergdahl (1984) and Tremblay (1988), whose papers also include an enumeration of the advantages and disadvantages of the measuring systems and deal with different aspects of pore pressure measurement such as the choice of instruments, installation problems, reliability, etc...

Hvorslev (1951) was the first to study the response characteristics of different piezometers. These characteristics are very important to consider in the choice of the appropriate measuring system. The reponse time of a measuring system is the time observed between the occurrence of a change in pore pressure at a certain point in the ground and the registration of the new pressure by an instrument situated at this point. This delay, called "response time", is due to the fact that a certain volume of water must flow between the soil and the filter tip in order to activate the measuring system of the piezometer and register the pressure change. The equalization process, which is governed by the response characteristics of the piezometer and the soil properties, has been formulated by Hvorslev (1951) assuming that the soil surrounding the piezometer is isotropic, fully saturated and infinite in extent, that no swelling or consolidation occurs and that there are no hydraulic losses in the system. If the pressure in the system differs from the true steady pressure in the ground by a value p_0 at time t=0, and the pressure difference is equal to p at time t, the response rate is as follows:

$$\frac{p_0 - p}{p_0} = 1 - \exp\left(-Fkt/V\gamma_w\right) \quad (1)$$

where F = the shape factor which depends on the shape and the dimensions of the filter element;

V = the volume factor which is the volume change necessary for the measuring system to register a unit change in pore pressure;

k = the soil permeability;

γ_w = the unit weight of water.

Among the different factors influencing the response time of a piezometer, the volume factor V is the easiest to measure and control. The volume factor of a measuring system denotes its flexibility. Table 1 gives different values of the volume factor for the most common systems presented by Peignaud (1977). Another study performed by Penman (1960) using the testing apparatus presented in Figure 1 and the piezometers shown in Figure 2 has given interesting results regarding the response time of different systems. Table 2 shows the time necessary for the systems studied to reach a given degree of stabilization.

Table 1. Different values of the volume factor for the most common systems after Peignaud, 1977.

TYPE OF INSTRUMENT	$\lambda = \frac{dv}{dp}$ (cm^3/kPa)
- Electrical transducer	$\lambda = 1 : 10^{-5}$
- Manometer	$\lambda = 25 : 10^{-5}$
- Open tube, diameter = 8 mm	$\lambda = 5$
diameter = 30 mm	$\lambda = 80$

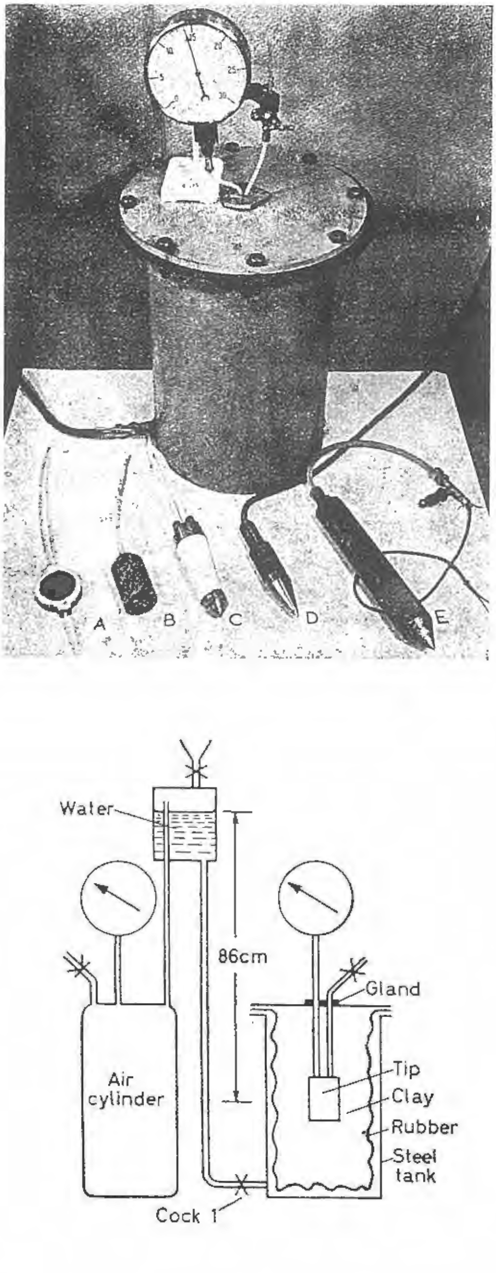


Fig. 1. Testing apparatus used by Penman, 1960.

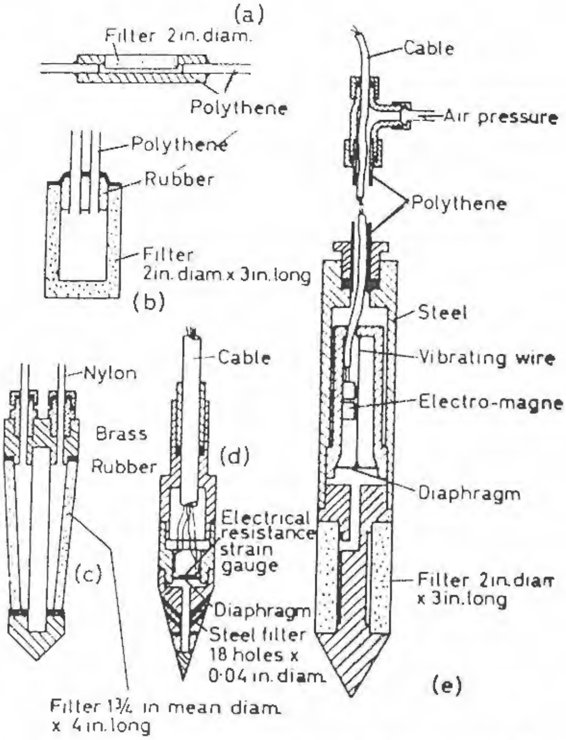


Fig. 2. Piezometers studied by Penman, 1960.

Table 2. Properties of the piezometers and their theoretical response times (Penman 1960).

Piezometer No.	1	2	3	3a	4	4a	5	6
Tip No.	B	A	B	B	C	C	D	E
F cm	40·1	14·0	40·1	40·1	40·9	40·9	13·5	40·1
V cm³/g × 10^{-4}							0·018	0·052
1 mm standpipe	78·5							
Bourdon gauge		1·16	1·16	1·16	1·16	1·16		
Connecting tubes		0·13	0·10	0·10	0·023	0·023		
340-ft nylon tube				4·96				
980-ft polythene tube						58·7		
t minutes when $k = 3{\cdot}4 \times 10^{-8}$ cm/sec								
$t_{99{\cdot}99}$	885	41·4	14·2	70·0	13·1	661	0·61	0·59
$t_{99{\cdot}9}$	664	31·1	10·7	52·5	9·8	496	0·46	0·44
t_{99}	441	20·7	7·1	34·9	6·5	330	0·30	0·29
t_{95}	288	13·5	4·6	22·8	4·2	215	0·20	0·19
t_{90}	221	10·3	3·6	17·5	3·3	165	0·15	0·14
t_{80}	155	7·3	2·5	12·2	2·3	115	0·11	0·10
t_{50}	66	3·1	1·1	5·2	1·0	50	0·05	0·04
t_{10}	10·5	0·5	0·2	0·8	0·2	7·9	0·01	0·01

Gibson (1963) introduced soil compressibility in the evaluation of the response characteristics of the piezometers. He was followed by Premchitt and Brandt (1981) who studied spherical piezometers and later extended their analysis to cylindrical piezometers (Brandt and Premchitt 1982).

Another problem discussed in the literature is the difficulty of obtaining a complete pore pressure profile using regular piezometers due to the problem arising through the installation of several instruments. When a complete profile is needed, three different installations can be chosen, Figure 3. The use of a multiple piezometer as presented in WESTBAY (1983) is preferable since it considerably diminishes the installation cost. However, this type of installation may be influenced by leakage along the pipe and it is therefore important to use inflatable packers between the filter areas for preventing the water travelling this way (Tao et al 1980). Another type of multiple piezometer presented in Figure 4 was used by Carpentier and Verdonck (1986), who obtained satisfactory results when measuring the pore pressure at different levels in a single installation.

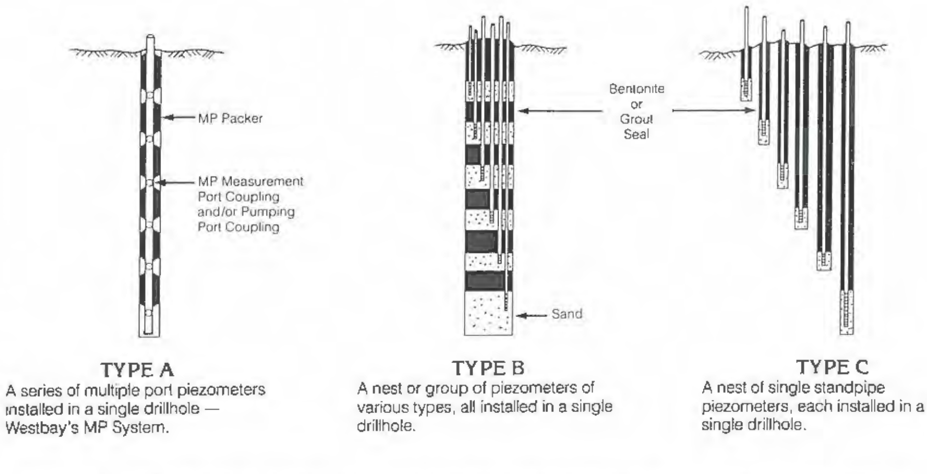


Fig. 3. Different types of measuring installation for measurement of pore pressure profile (WESTBAY 1983).

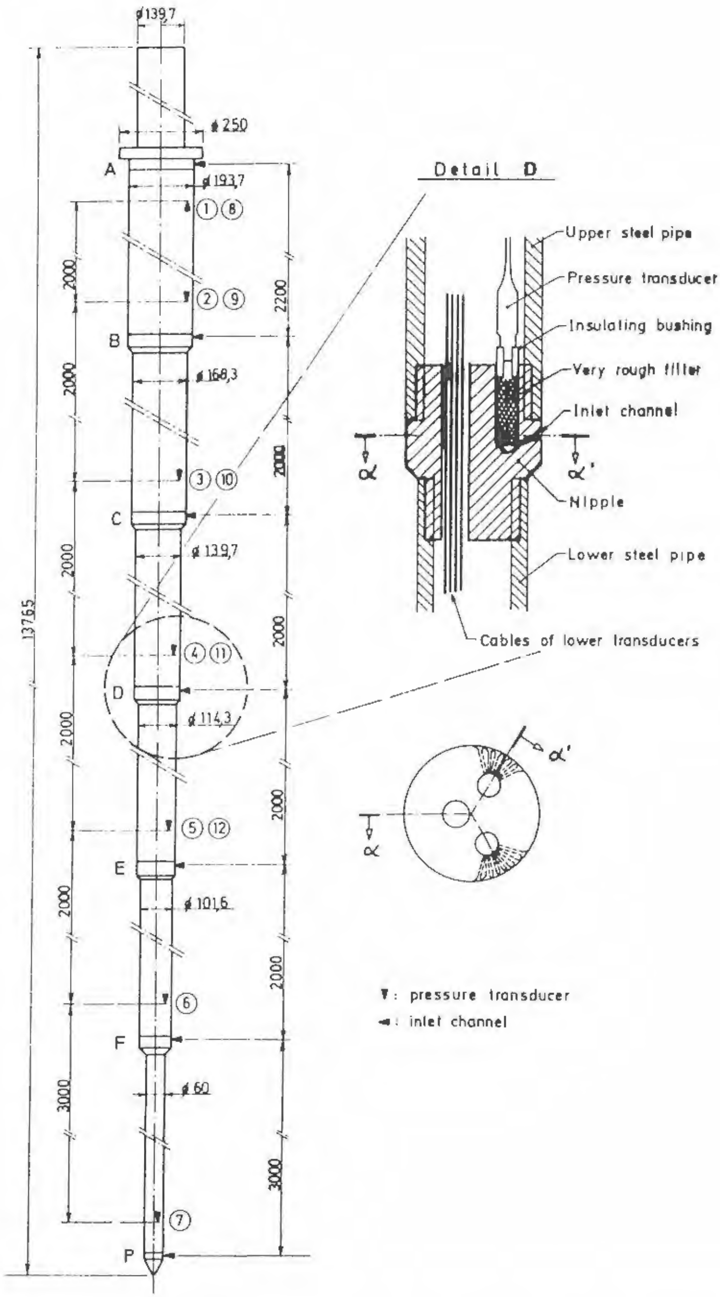


Fig. 4. Multiple piezometer used by Carpentier and Verdonck, 1986.

2.2 LONG-TERM MEASUREMENTS

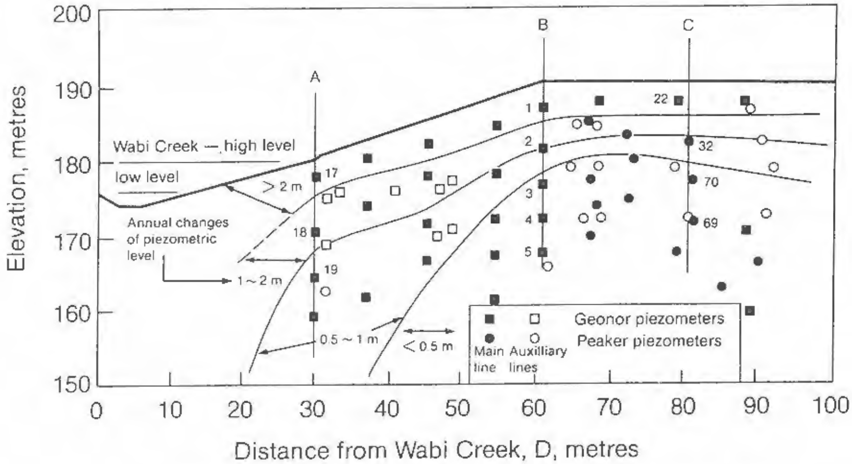
The next step in this literature survey includes an overview of the long-term measurement of pore pressure. Kenney and Chan (1977) and Kenney and Lau (1984) present the results from one of the few documented projects with long-term measurement. The results shown in Figure 5 clearly indicate a seasonal variation in the pore pressure. It is also interesting to note the amplitude of these variations in different piezometers, the intruments installed at greater depth showing a smaller fluctuation than those near the surface. The authors concluded that the zone situated below 4.5 m is nearly unaffected by rainfall or seasonal changes in the groundwater level. Similar conclusions are made by Hansbo (1987).

Other results presented by Berntson (1983) do not show the same phenomena regarding the fluctuations in pore pressure with depth, Figures 6 and 7. Almost all the sites investigated by Berntson have shown fairly constant fluctuations in pore pressure over the entire deposit, which is a significant difference compared with the results obtained by Kenney and his colleagues.

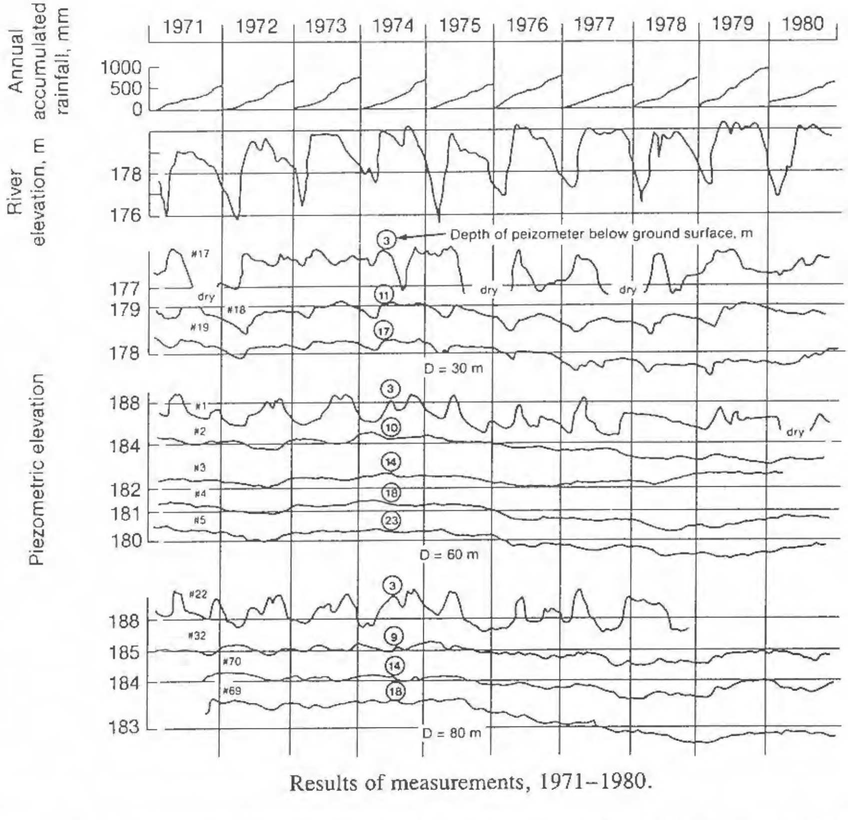
2.3 PORE PRESSURES IN NATURAL SLOPES

Lafleur and Lefebvre (1980) analysed the influence of the pore pressure distribution and the hydraulic gradient in the vicinity of a slope on the effective stresses normal to a failure surface, and thereby the influence on slope stability. The modelling technique used in the study (Figure 8) and supported by field data from four test sites, showed that the stability of the slope is greatly influenced by the pore pressure distribution, which should therefore be defined with precision.

The use of excess pore water pressure measurement as a method for controlling stability is being studied with interest by several researchers (Bauduin and Moes 1987, Bergdahl and Tremblay 1987). The relationship between the rainfall regime, the pore pressure and the displacement rate of natural slopes has already been demonstrated in several studies. Bertini et al (1987) presented two cases in Italy, where such interaction was clearly observed, Figure 9. Dauncey et al (1987) showed that the same principle may be applied to the stability of embankments, the pore pressure increasing significantly in the zone of failure, Figure 10. These observations support the idea that pore pressure measurement offers a very useful tool in monitoring unstable slopes, provided that the installation is performed properly using the appropriate instruments.



Locations of piezometers and annual changes of piezometric level.



Results of measurements, 1971–1980.

Fig. 5. Long-term measurements of pore pressure at Wabi Creek (Kenney and Lau 1984).

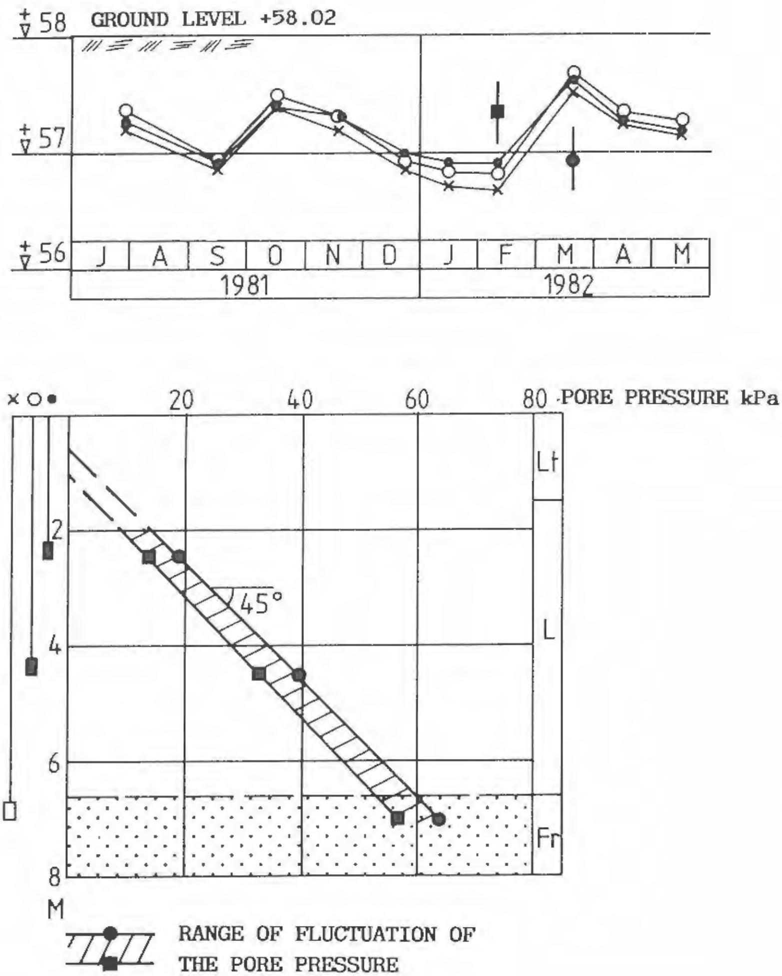
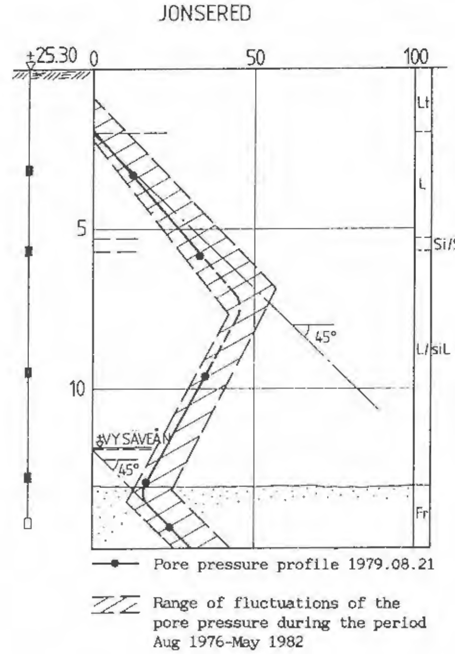


Fig. 6. Variations in a typical pore pressure profile (Berntsson 1983).



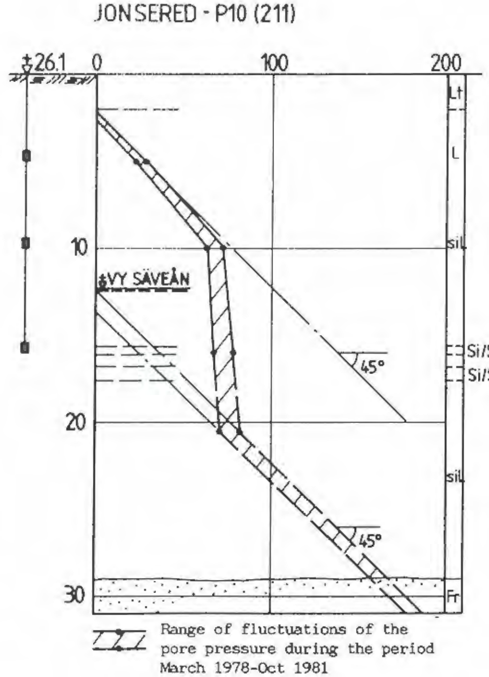


Fig. 7. Variations in pore pressure profile on two sites in Jonsered, Sweden (Berntsson 1983).

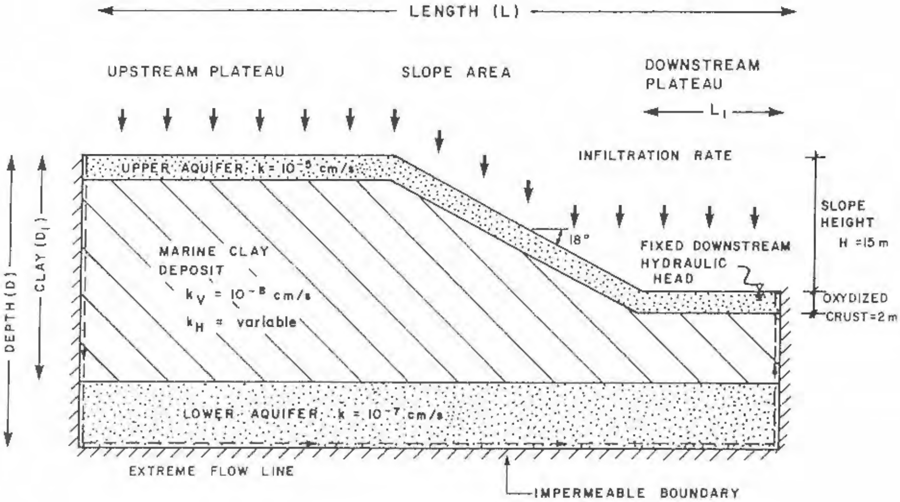
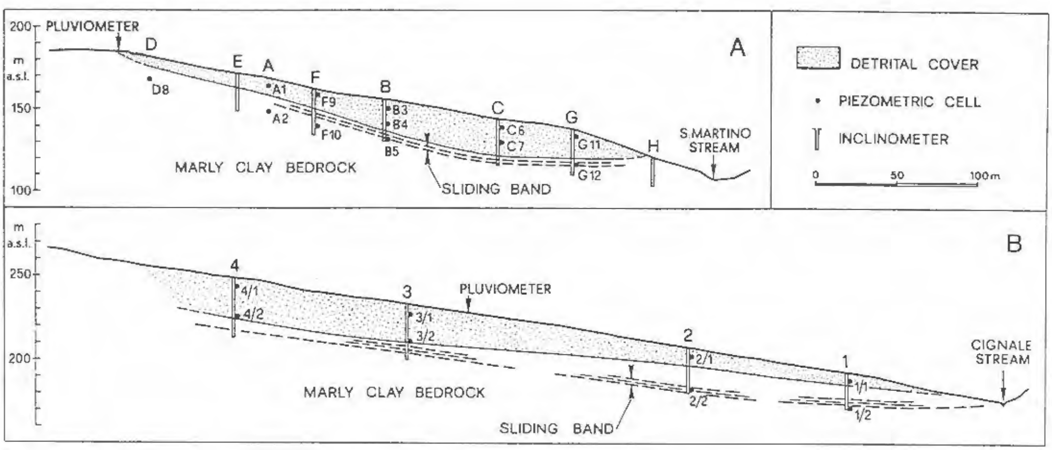
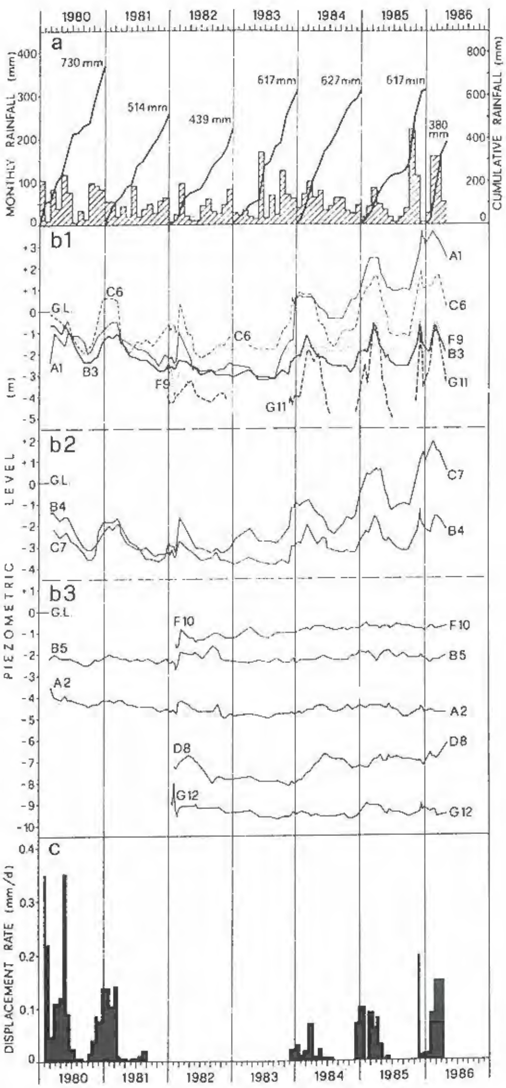


Fig. 8. Flow net used by Lafleur and Lefebvre, 1980.

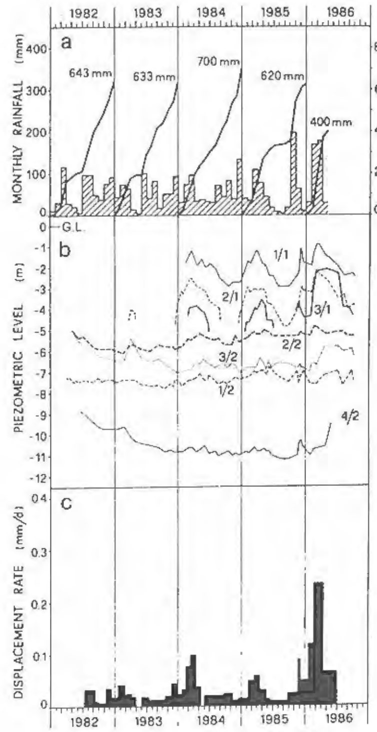


S.Martino (A) and Cignale (B) geological cross sections and field instrumentation.

Fig. 9a. Geological cross sections and field instrumentation of two sites investigated in Italy (Bertini et al 1987).



S. Martino area: pluviometric (a), piezometric (b1=superficial cells in the cover; b2=in depth in the cover; b3=cells in the bedrock), and displacement rate (c) data



Cignale area: pluviometric (a), piezometric (b=all the cells), and displacement rate (c) data

Fig. 9b. Correlation between rainfall, pore pressure and displacement rate (Bertini et al 1987).

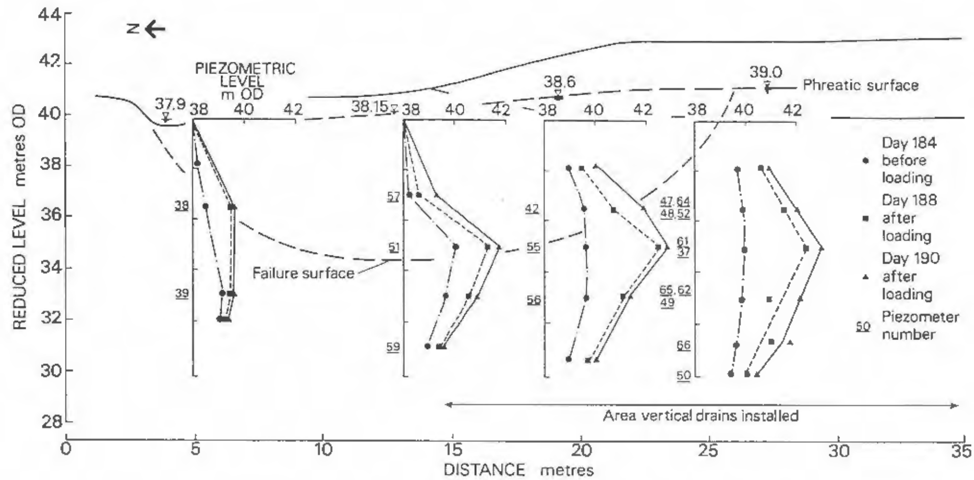


Fig. 10. Variations of pore pressure under a test embankment in Athlone, Ireland (Dauncey et al 1987).

3. METHODS FOR MEASUREMENT OF PORE PRESSURE

3.1 INTRODUCTION

It is a common practice to estimate the pore pressure distribution in a deposit by measuring the level of the water table in an open borehole and to assume a hydrostatic distribution. However, since the pore water pressure may adopt different configurations depending on the site conditions, this practice may lead to errors which can create serious problems and sometimes even endanger the stability of a construction. These problems are especially important to consider if the soil is under the effect of a strong hydraulic gradient or if a confined aquifer is encountered in the deposit. It is therefore important for the engineer to investigate and to take into account the groundwater conditions when analysing geotechnical problems.

3.2 OBSERVATION WELLS VS PIEZOMETERS

The water conditions of a site may be investigated by using instruments falling into two different categories, observation wells for measurement of groundwater level and piezometers for measurement of pore pressure at a specific level in a soil deposit.

The observation well is usually affected by the pore water pressure along the total length of the hole. The most common version is the uncased borehole (Figure 11a), but even boreholes with casing may be classified in the same category (Figure 11b). The observation well gives only an average head existing over the length of the well and the presence of a confined aquifer or a layer with artesian pressure will affect the measurements, which may therefore be of little significance. The use of a casing in the open borehole will eliminate the problem of the influence of different layers only if the space between the casing and the soil is filled with bentonite or other sealing material; the presence of the casing then allows measurement of the pore pressure at the bottom of the borehole.

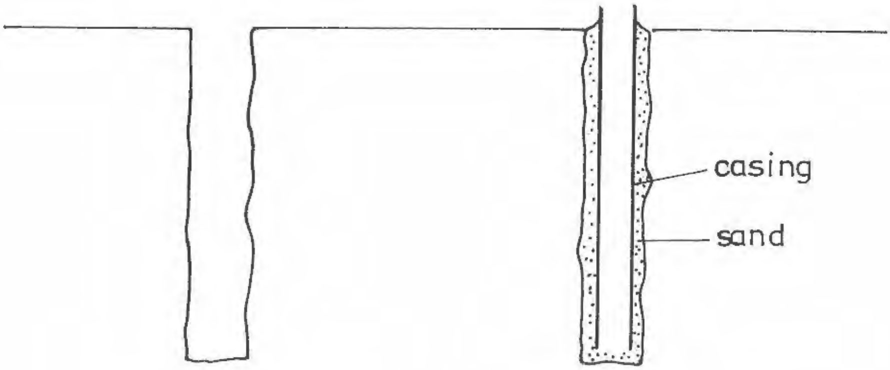


Fig. 11. Schematic of observation wells.

When a more accurate measurement of the pore pressure is needed, the use of a piezometer is necessary. The piezometer, the principle of which is presented in Figure 12, enables the measurement of pore pressure at any specific level. The main part is a filter tip which is in direct contact with the pore water through a porous element. The pressure inside the filter tip is constantly adjusted to the pore water pressure (u) at this level since any variation of pressure is transmitted directly through the filter. The filter tip can be installed in the soil by lowering it into a borehole in a cavity filled with coarse material and sealed with e.g. bentonite plugs, Figure 13a. However, when measuring pore pressure in a soft soil, it is often sufficient to push or drive the filter tip into the deposit from the ground surface without the need for any additional sealing, Figure 13b.

The second part of the piezometer is the pressure measuring device used to record the pressure in the filter tip. According to the basic principle of this device, there are two major classes of piezometers, the open and the closed systems, which can also be divided into several sub-classes.

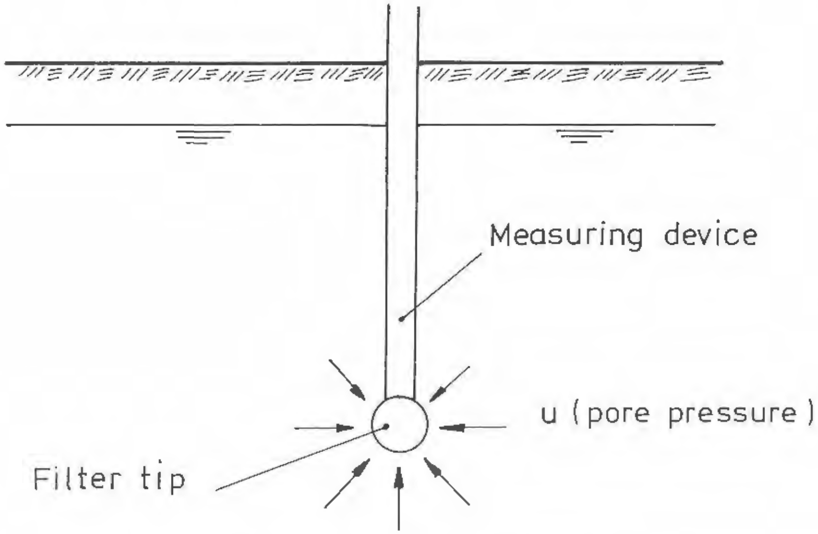


Fig. 12. Schematic of piezometer.

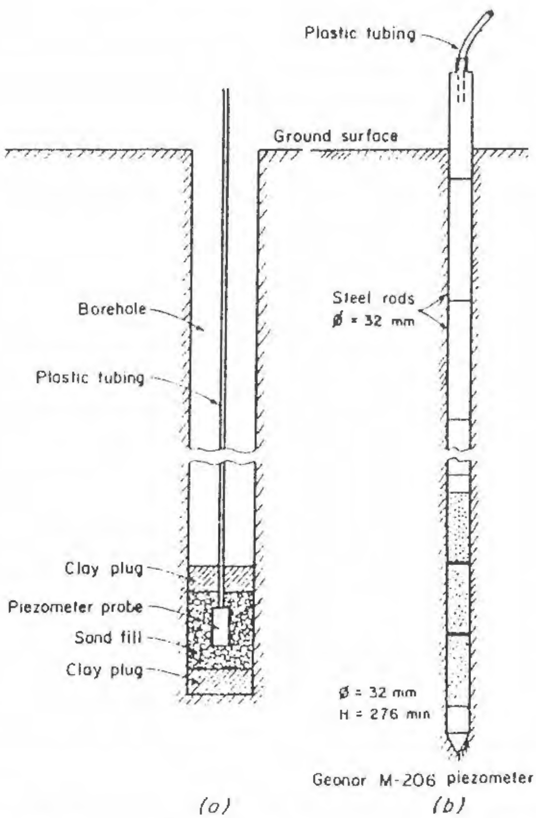


Fig. 13. Methods for installation of the piezometer (Tavenas et al 1986).

3.3 OPEN SYSTEMS

3.3.1 Principle

The open system is based on the principle that the water under pressure in the filter tip, when allowed to rise in a pipe, will stabilize when the water level corresponds to the potential at the filter level, Figure 14. Two different types of open systems are available: the perforated pipe and the standpipe piezometer. The open systems are characterized by a low cost and a relatively long time lag. They are mostly used in friction materials.

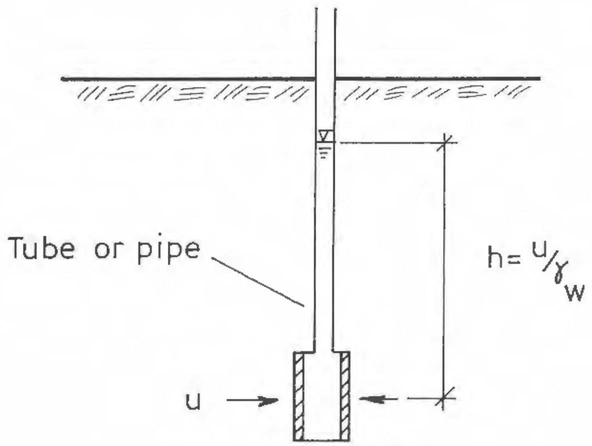


Fig. 14. Schematic of open system.

3.3.2 Perforated pipe

In soils with high permeability, a pipe perforated over a certain area may be used to measure the groundwater level, Figure 15. The diameter of the pipe may vary from 10 to 40 mm, the most common system being a 25 mm water pipe. The pipe is usually plugged at the bottom and perforated over a length of about 0.2 m. Coarse sand is used to fill the perforated pipe and acts as a filter element. The measurements are performed by lowering a device which sends a signal when it reaches the water in the tube. The signal transmitted may be a sound produced by a specially shaped device or an electrical signal send through a coaxial cable. The perforated pipe has a long time lag and should therefore be used only for measuring the groundwater level in soils with high permeability.

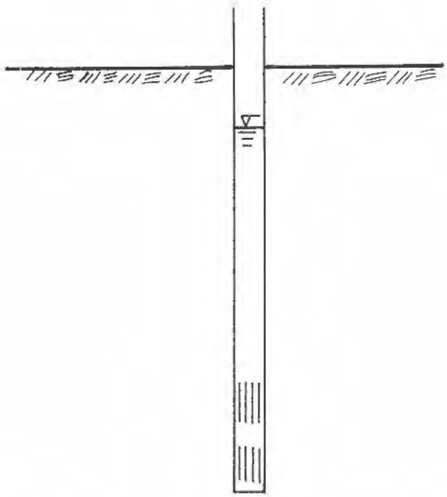


Fig. 15. Schematic of perforated pipe.

3.3.3 Standpipe piezometer

The standpipe piezometer (or open standpipe) is certainly the most common system used in practice for measuring pore pressures. As shown in Figure 16, the piezometer is composed of a filter tip to which a plastic tube is connected so that the water can circulate, in both directions, between the tip and the surrounding soil. The diameter of the tube may vary from 4 to 8 mm and should be chosen with regard to soil permeability. The stabilized water level in the tube, corresponding to the potential at the filter elevation, is measured from the ground surface by lowering within the tube a coaxial cable connected to an amperemeter or other reading instrument.

Since the diameter of the plastic tube is much smaller than the diameter of the perforated pipe, the volume of water in movement during the registration of pore pressure fluctuations is much smaller, and therefore the response time is much lower. The open standpipe piezometer is usually installed in sand and silt. It can sometimes be used in clays if the variations are slow enough for water movement to occur between the soil and the filter tip without delay, or if it is possible to wait for stabilization before the measurement (3-6 weeks).

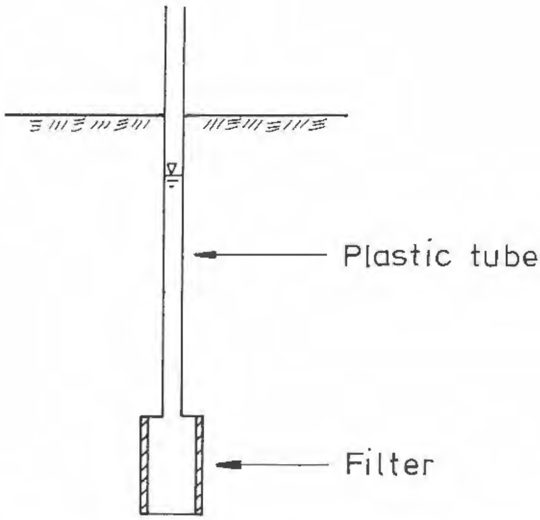


Fig. 16. Schematic of open standpipe piezometer.

3.4 CLOSED SYSTEMS

3.4.1 Principle

The basic principle of the closed system is that any variation in the pore pressure at the filter level is registered almost instantly in the whole system, Figure 17. The measuring device of the closed system requires the movement of a small volume of water for the registration of a pressure variation. Therefore, the closed system has a much shorter response time than the open system and can be used in soils with lower permeability.

3.4.2 Hydraulic piezometer

The standpipe piezometer may be converted into a closed system by filling the open tube with water (or other fluid), and closing it with a valve at the ground surface; this system, shown in Figure 18, is named the hydraulic piezometer. The pressure in the filter tip is measured by using a manometer or a gauge connected to the tube; the reading instrument may be installed permanently on the tube or connected only when measurement is performed.

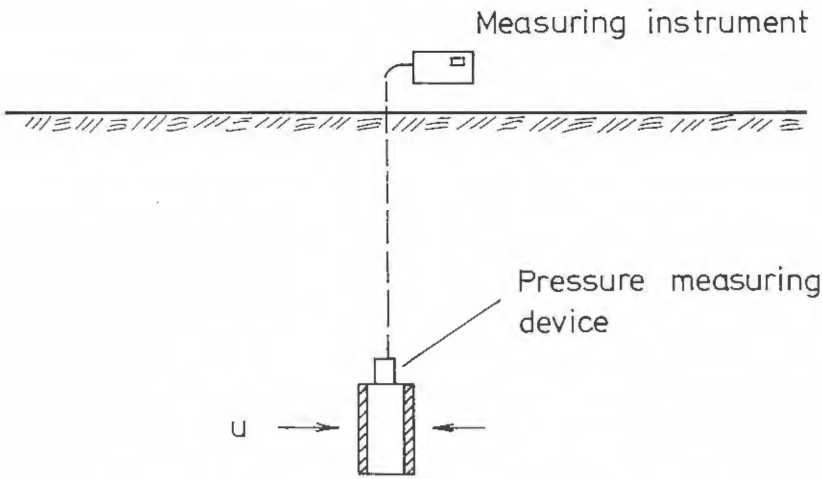


Fig. 17. Schematic of closed system.

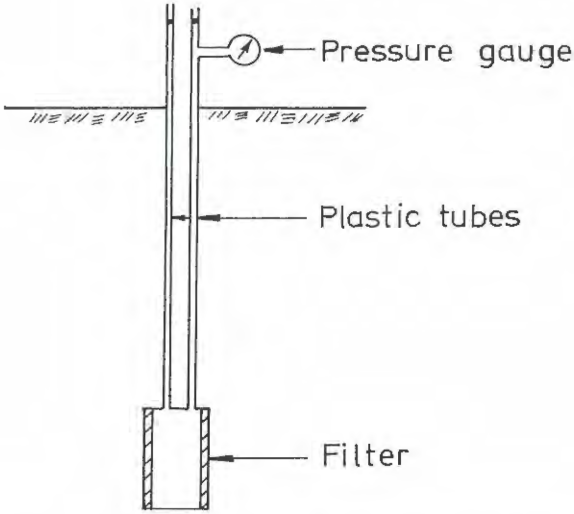


Fig. 18. Schematic of hydraulic piezometer.

The conversion of a standpipe piezometer to a hydraulic piezometer is interesting in two particular cases:

- when the open system has a response rate which is too slow to give a correct estimate of the variations in pore pressure;
- when the piezometer is installed in a layer under the effect of artesian pressure so that the water flows out of the open tube.

To give a correct value of the pore pressure, the tube reaching the surface must be perfectly saturated; the hydraulic piezometer should therefore be equipped with a double pipe, which can be used for making the water circulate and thereby eliminate air bubbles in the system.

Since the temperature will influence the pressure in the tube, it is also important to protect the lines from any change in temperature, especially the section located near or outside the ground surface.

3.4.3 Pneumatic piezometer

The pneumatic piezometer consists of a filter tip equipped with an air-activated valve on top of the chamber, two tubes, a pressure gauge and an air/gas supply, Figures 19 and 20. The most common air valve used in these systems is a flexible membrane which prevents the communication between the two tubes. To measure the pressure in the chamber, a flow of compressed air/gas is admitted into one of the tubes. When the air/gas pressure equals the pore pressure, the membrane relaxes and allows circulation from the inlet line to the outlet line. According to Dunnicliff (1981) the air/gas supply is then shut off and the circulation stops when the membrane is pressed back against the wall. At this moment, the pressure in the first line equals the pressure applied on the membrane and can be read on the manometer installed on the line.

Another procedure for evaluating the pressure in the chamber is to submerge the end of the outlet line in a water bath in order to control the air/gas flow (see Figure 19). The circulation can be observed at ground level when air/gas bubbles are rising in the water bath. The pressure is registered when the bubbles are rising at a constant specific rate. Some pneumatic piezometers are equipped with a flow controller instead of a water bath, for controlling the air/gas circulation (see Figure 20). The flow controller is connected to the inlet line and ensures that a constant flow is injected during the measuring procedure.

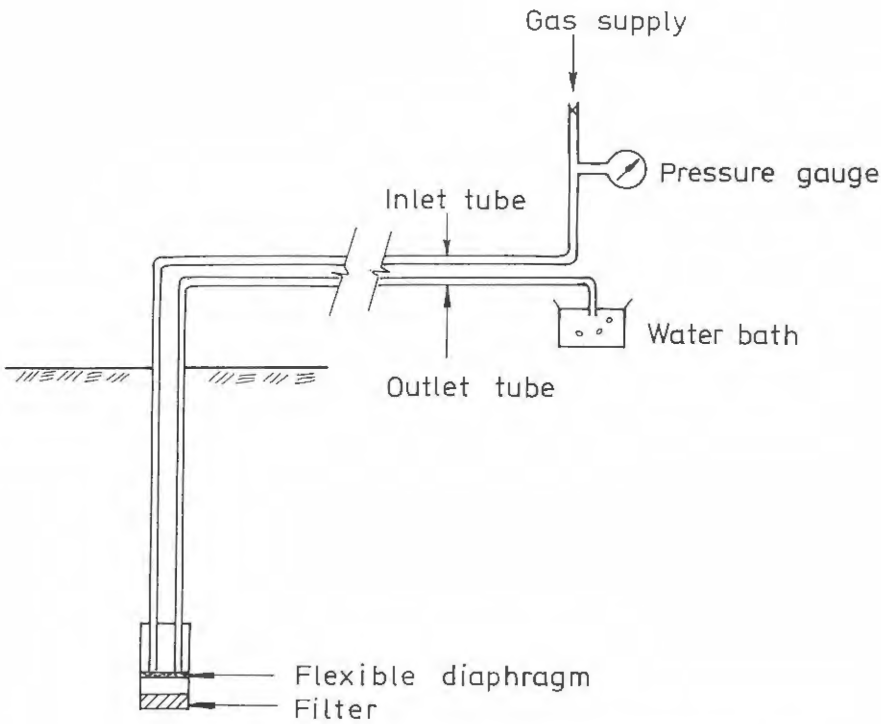


Fig. 19. Schematic of pneumatic piezometer with water bath.

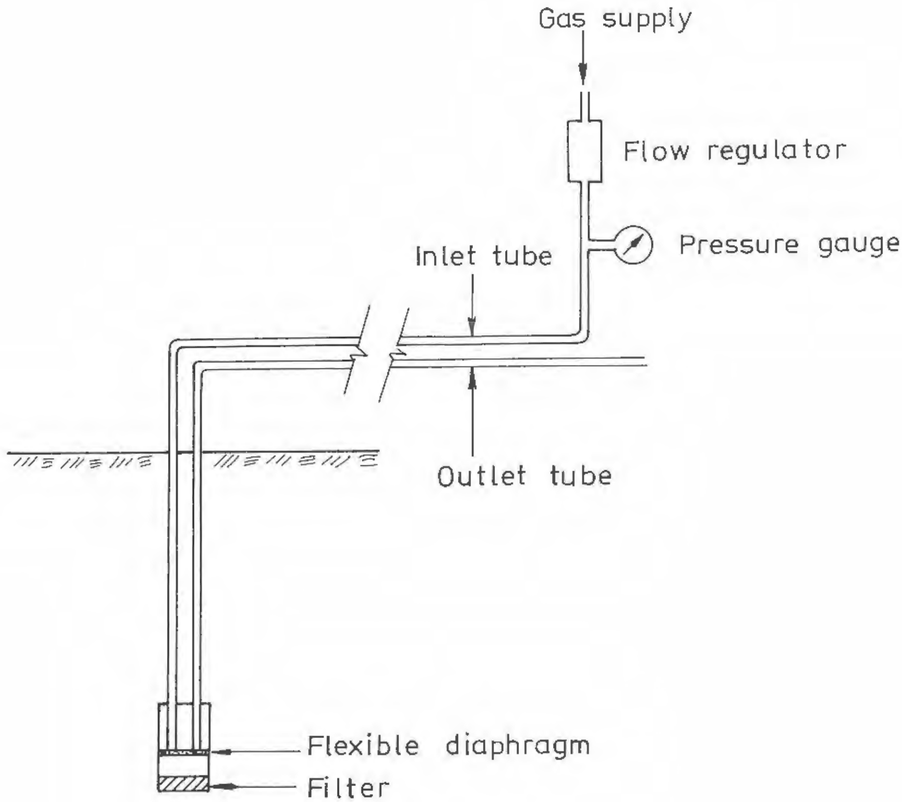


Fig. 20. Schematic of pneumatic piezometer with flow controller.

There are also more sophisticated types of pneumatic piezometer, where a valve is used instead of a flexible diaphragm for control of the flow between the lines (see Dunnicliff 1981). The basic principle is the same except that the procedure is inverse: after shutting off the air/gas supply, the flow is stopped by the closure of the valve and the pressure in the exit line is then equal to the pore pressure.

Since it forms a closed system, the pneumatic piezometer requires small water movements to respond to any variation in pore pressure; the time necessary for stabilization is therefore very short. Although a certain volume of water must be displaced during the measuring procedure, this volume is very small and the restabilization time is often negligible. The long-term stability and the simplicity of the equipment are other important advantages of the pneumatic piezometer.

3.4.4 Electrical piezometer

The electrical piezometer is based on the principle that pressure applied on a membrane located in the upper part of the filter tip will cause a deflection of the membrane which is proportional to the pressure applied. The measurement of the deflection may be performed by using either vibrating wire or electrical resistance strain gauges (Lindholm 1988).

The vibrating wire piezometer works according to the principle that the tension of a wire connected to the back of the membrane changes with any deflection of that membrane, Figure 21. The variation in the tension will result in a variation in the resonant vibration frequency. Measurement is performed by sending a current to the filter tip, creating a magnetic field near the wire which starts to vibrate at its new resonant vibration frequency. This frequency is registered on a frequency counter and the pressure in the tip is evaluated by using a calibration curve obtained before the installation of the piezometer. Among the many different types of vibrating wire piezometers available, the piezometers of the Geotech and Geonor types are the most commonly used in Sweden, Figure 22a and 22b.

Some versions of vibrating wire piezometer are equipped with a special device for controlling the zero-value (frequency when no pressure is applied on the membrane) after installation. In the Geotech piezometer, this control is performed by releasing the tension in the wire using a magnetic field, Figure 23a. The version developed by Geonor uses a back-pressure to remove the rubber membrane from the steel membrane to which the wire is connected, Figure 23b.

In the electrical resistance strain gauge piezometer, the deflection of the membrane is also used to measure the pressure in the filter tip. A gauge formed of a single thread is usually fixed on the back of the membrane so that any deflection affecting the membrane will alter the length of the thread, thereby changing its electrical resistance, Figure 24. The pressure is measured by reading the resistance of the gauges and reading off the corresponding pressure on a calibration curve.

There is no possibility of controlling the zero-value of the resistance strain gauge piezometer after installation. However, the membranes and gauges used in its fabrication are made of such material that they often remain stable over longer periods than the vibrating wire piezometer.

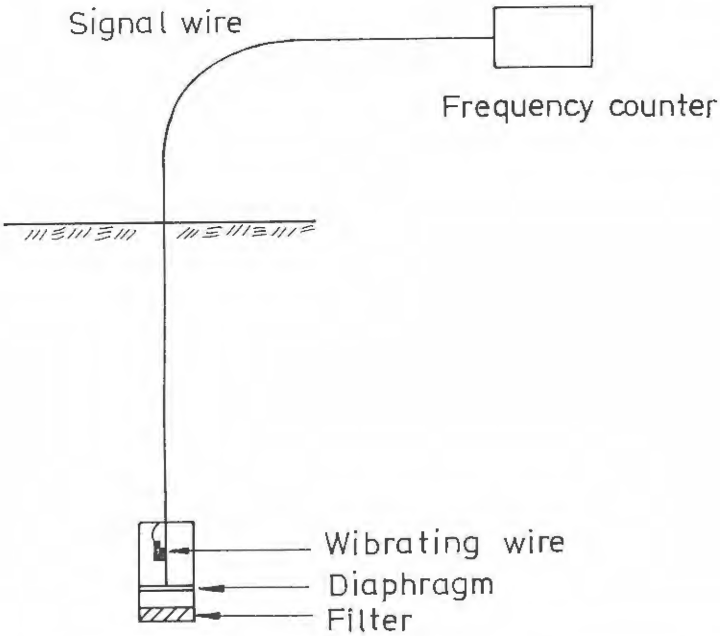


Fig. 21. Schematic of electrical piezometer - vibrating wire.

When using an electrical piezometer, it is important to know what pressure is read by the instrument. Some types of piezometer, such as the Geotech vibrating wire piezometer, register the absolute pressure, which must be corrected for the atmospheric pressure at ground level during the measurement. Other types, such as the Geonor vibrating wire, make the correction in the filter tip and the pressure measured is relative to air pressure at ground level. For the absolute pressure piezometer, it is important to note the atmospheric pressure when performing the calibration, since this value will be necessary for the correction of the measurements.

The electrical piezometer is a rather expensive system, although it presents the advantages of short response time and simple reading procedure. In the past, this type of piezometer has been subject to problems of instability and zero drift when used over long periods; however, the development of filter tips with in-place calibration check and the use of more appropriate material has eliminated these problems.

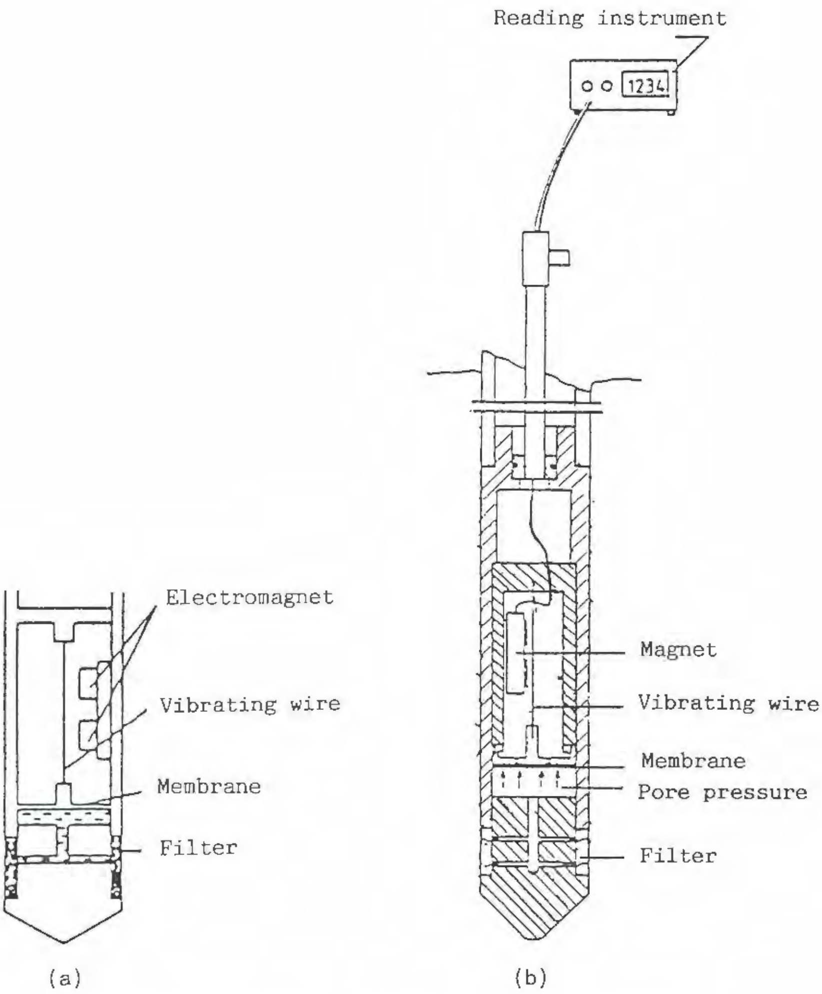


Fig. 22. (a) Geotech (b) Geonor
Different types of vibrating wire piezometer.

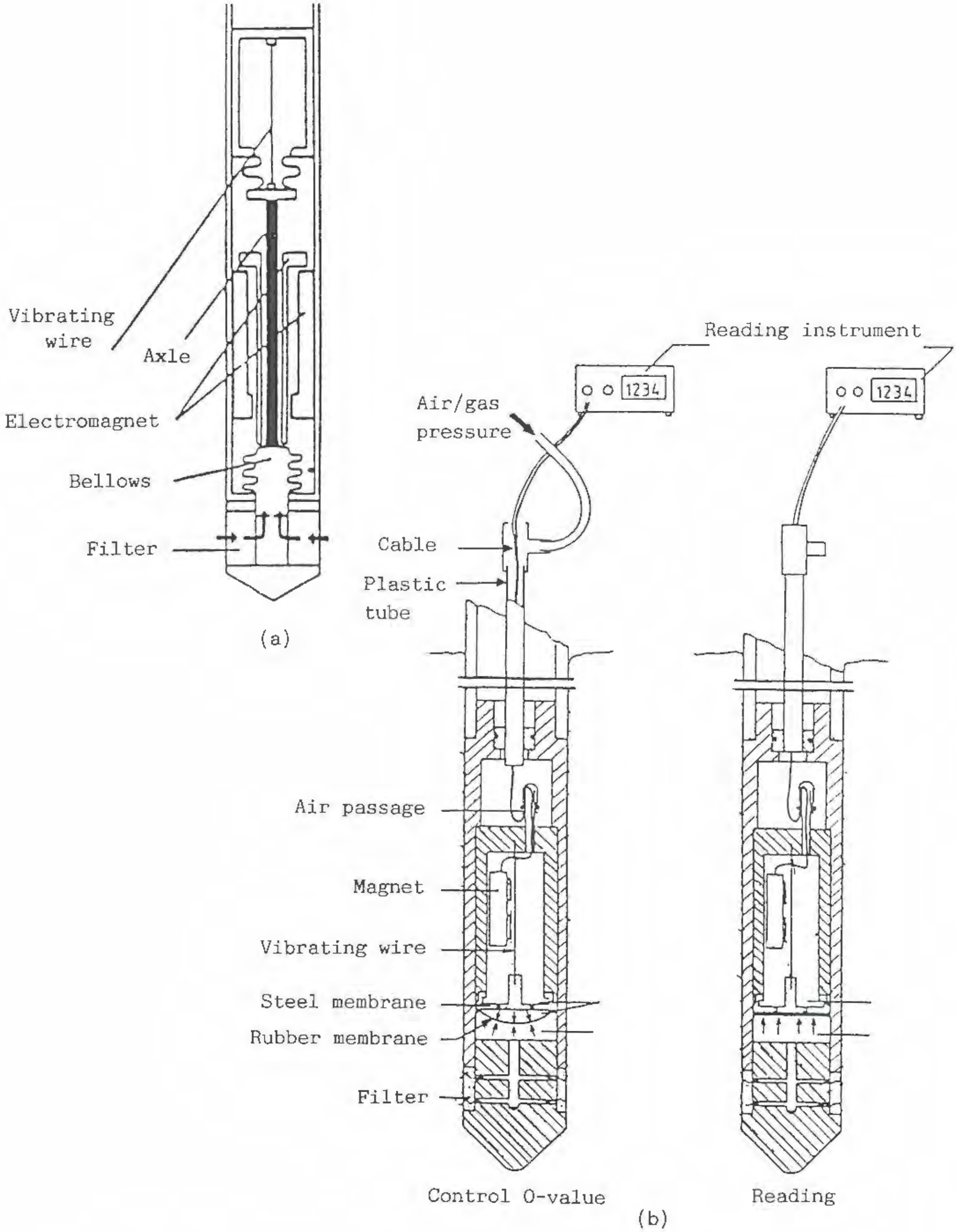


Fig. 23. (a) Geotech (b) Geonor
Different types of vibrating wire piezometer with zero-control.

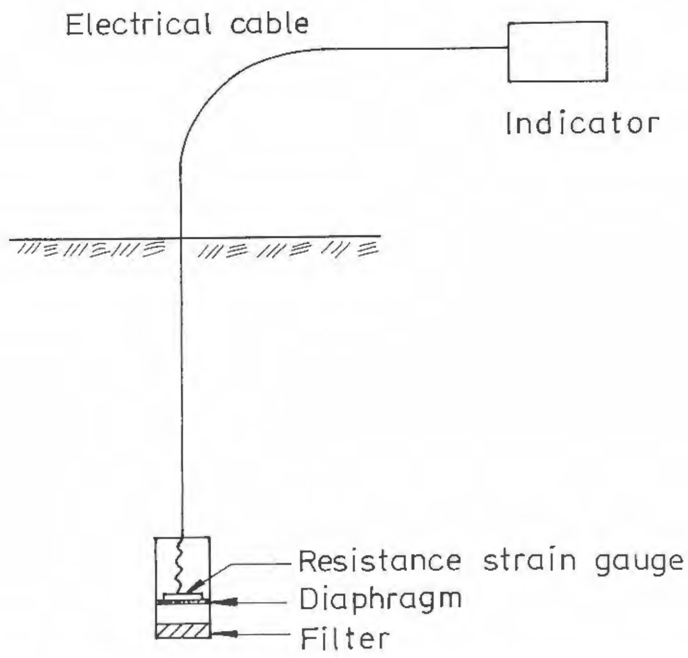


Fig. 24 Schematic of electrical piezometer - resistance strain gauge.

3.4.5 BAT piezometer

The BAT piezometer is a closed system comprising a special filter tip, a pressure transducer and a read-out unit (BAT 1985). The filter tip presented in Figure 25 is formed essentially of a porous element and a chamber closed at the top by a rubber disk. To perform measurement of the pressure in the chamber, a transducer is lowered onto the tip and a hypodermic needle fixed on the transducer penetrates the rubber disk. After the penetration, the needle provides communication between the chamber and the transducer, and the pressure is read at the ground surface.

The main advantage of this system is that the pressure transducer does not have to be installed permanently, but may be removed at any time to verify the zero value and the calibration. In permanent installations, any damaged transducer can easily be removed and replaced. In non-permanent installations, it is possible to use only one transducer regardless of the number of filter tips installed in the ground.

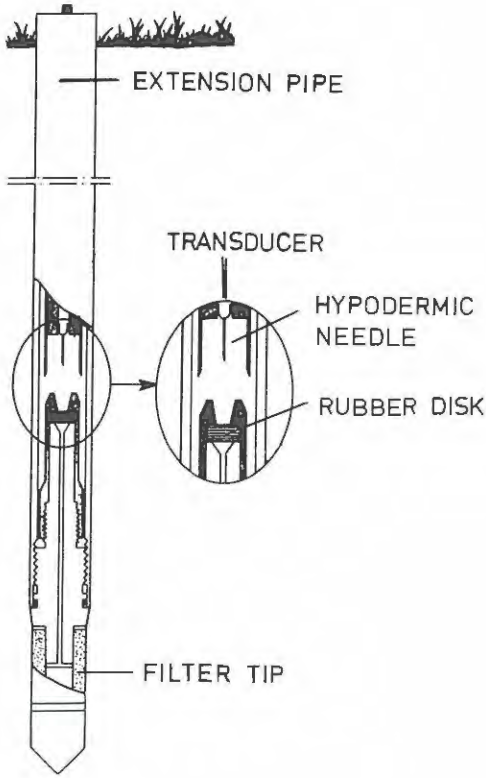


Fig. 25. BAT piezometer.

During the reading procedure, the penetration of the needle through the rubber disk creates a disturbance of the pressure in the tip and stabilization may sometimes take some minutes, especially in fine-grained soils. To diminish this problem, a damping device which contains air bubbles is usually installed in the filter tip to absorb the pressure variation without disturbing the water pressure in the tip. The connection of the transducer onto the tip may also lead to some problems; it is very important to make sure that the needle penetrates the membrane fully when measurements are performed.

3.5 CONCLUSIONS

Since every change in pore pressure is followed by water movement between the filter tip and the soil, there is always a delay between the change in pore pressure and measurement of the new pressure by the piezometer. This delay depends mostly on the volume factor of the measuring system and the soil permeability. Open systems are adequate and efficient in soils with high permeability. However, they are not recommended when important variations in pore pressure are expected in less permeable soils, since the stabilization of the water level in the tube may take a relatively long time (3 to 6 weeks according to Swedish experience). In this situation, closed systems are more reliable because of the small volume of water in movement necessary for the registration of a variation in pore pressure.

The main advantages of the open systems are the low cost of the instruments and the simplicity of the principle of measurement. They are relatively easy to install, but they have a longer response time and are less accurate than closed systems.

Closed piezometers can be connected to automatic recording systems and it is possible to install the reading device far away from the piezometer, which is very convenient when pore pressures are measured on a construction site or when large areas are monitored. The main disadvantage of the closed systems is that they are more expensive than open piezometers. Moreover, they generally demand more careful handling during transport, installation and reading; therefore, specially trained field personel must be used to perform these tasks.

4. SOURCES OF ERROR IN PORE PRESSURE MEASUREMENT

4.1 INTRODUCTION

Several sources of error have to be considered when measuring pore pressures and many of them are particularly important when variations in pore pressure are observed. Figure 26 presents some of the major sources of error as given by Hvorslev (1951).

The effect of some sources of error can be diminished or even eliminated by choosing appropriate instruments or by careful handling. However, certain problems are unavoidable and must be considered in the interpretation of the measurements.

4.2 GENERAL SOURCES OF ERROR

4.2.1 Stress adjustment time lag

The installation of a piezometer in a deposit disturbs the soil structure and changes the soil conditions. The void ratio and the water content of the soil are changed, creating a flow of water from the tip of the surrounding masses, or vice versa. The time required for such movement to take place is called the stress adjustment time lag.

All the piezometers installed are affected by the stress adjustment time lag to different degrees, depending mostly on the mode of installation, the time lag being longer for a filter tip pushed or driven into the deposit than for a tip installed in a borehole. Other factors such as the degree of overconsolidation of the soil may also influence the stress adjustment time lag.

The stress adjustment time lag does not occur only after the installation of the tip, but may also be encountered when the stresses in the deposit are modified during the measuring period.

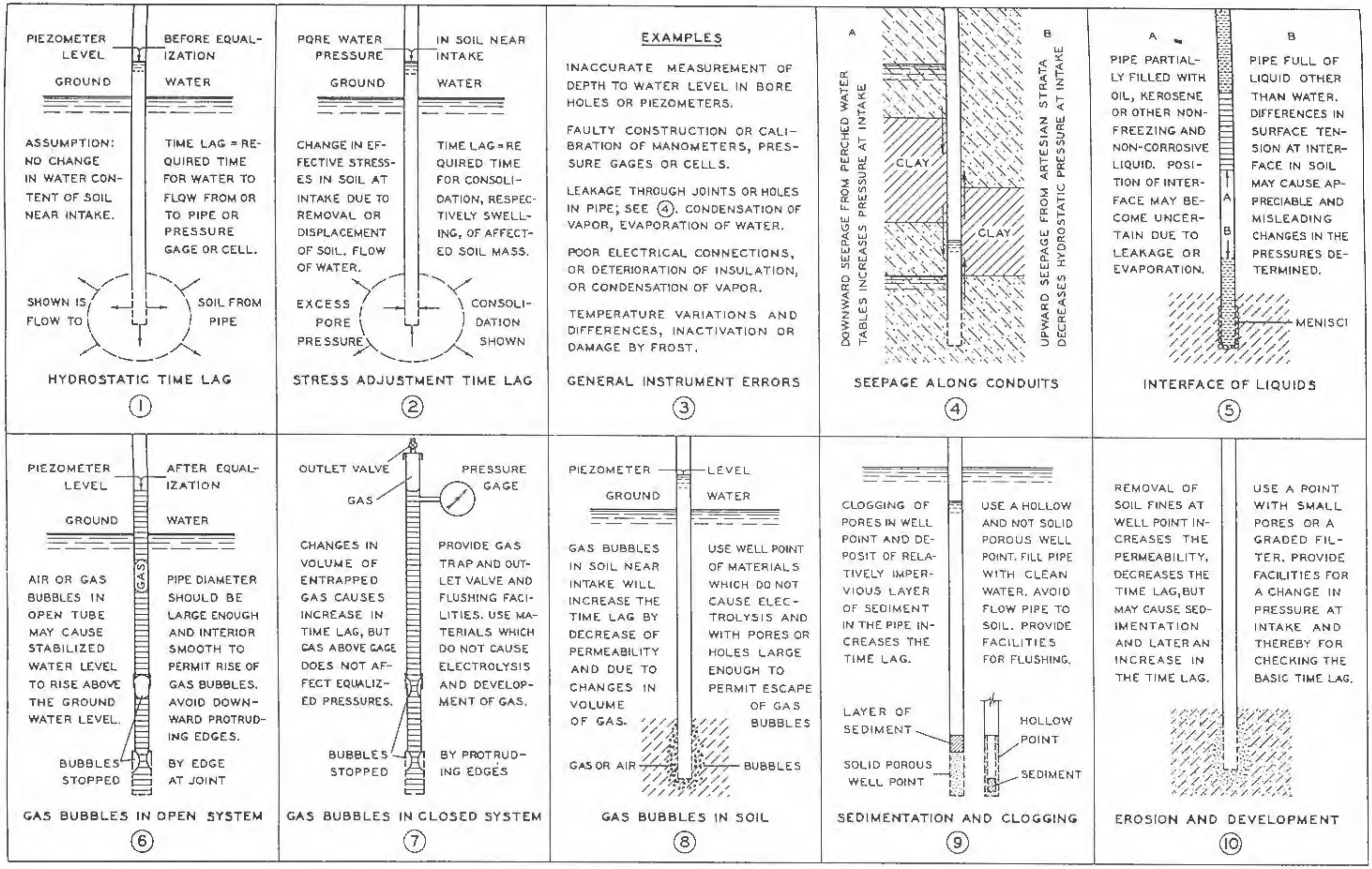


Fig. 26. Sources of error in pore pressure measurement (Hvorslev 1951).

4.2.2 Hydrostatic time lag

The hydrostatic time lag may be defined as the time required for the equalization of a difference of pressure between the piezometer and the surrounding soil. It is one of the most important sources of error since it affects every reading when the pore pressure varies.

The hydrostatic time lag depends on the soil permeability, the difference in pressure between the soil and the piezometer and the shape and dimensions of the filter element. Since the permeability of the soil and the pore pressure difference cannot be controlled, the only possibility of diminishing the hydrostatic time lag is by choosing the appropriate device.

The open system has, fundamentally, a larger hydrostatic time lag than the closed system, the volume of water in movement usually being more important. However, it is possible to decrease the hydrostatic time lag of an open system by using a larger filter area combined with a smaller tube diameter.

The hydrostatic time lag is a very important factor to consider when choosing a system for measuring pore pressure in a particular situation. In the case where variations are expected to take place within a very short period, closed systems, such as the electrical piezometers, are more adequate than open systems.

4.2.3 Seepage along conduits

The pore water pressure at the level of the filter tip may be affected by water communication between that level and the upper layers. When the filter tip is installed in an artesian layer, seepage along installation pipes and cables will result in a dissipation of the pore pressure near the tip. The measurements will always be lower than the actual pressure in the layer. The inverse situation, i.e. an increase in pore pressure, occurs when a perched water table is located over the tip level. The pore pressure near the piezometer will also increase if the infiltration water is able to reach the tip by flowing along the conduits.

In soft soils, seepage along conduits is greatly diminished or even totally eliminated by pushing the piezometer into the deposit after preboring to the groundwater level. The soil displaced by the passage of the point will seal the installation by reconsolidation along the rods. However, when tips are installed at shallow depths, it is preferable to seal the prebored hole in order to avoid infiltration of water from the ground surface. Bentonite mixtures and cement grouts may be used for this purpose.

If a filter tip is installed in a borehole, it is always very important to seal the hole carefully above the tip. The seal should be at least 0,5 m long, and bentonite is recommended as sealing material.

4.2.4 Sealing of joints and connections

The preceding section discussed the importance of eliminating any possibility of disturbance of pressure in the filter tip by water flow along the conduits and through the filter area. In the standpipe piezometer and the hydraulic piezometer, the disturbance may also originate from the top part of the chamber where water may infiltrate due to a bad connection between the tube and the tip. This connection must be carefully sealed, otherwise the pressure in the tip will only be representative of the water level in the rods. Moreover, all joints between two rods must be carefully tightened to avoid water leakage from the soil.

4.2.5 Gas or air bubbles in the system

The presence of air in the system has a considerable influence on the pore pressure measurements. The magnitude of the error is controlled by the volume of the air bubbles and their localization. The effect of air in the system also differs depending on whether an open or a closed system is used.

In the case of an open system, entrapped air filling the entire section of the line causes a rise in the water level in the tube above the groundwater level. Air bubbles in a closed system also influence the indicated stabilized pressure if they are located between the filter tip and the manometer, provided that they fill the entire tube section. Air above the pressure gauge or small bubbles on the walls of the lines do not affect the measurement. However, since the air is highly compressible, the time lag of a closed system will always increase if air bubbles are present in the system, no matter where they are located.

To avoid problems created by the pressure of air in a system used for pore pressure measurements, it is very important to saturate correctly the filter tip, the chamber and the lines before installation. The equipment must be handled with care, especially during transportation, and every precaution must be taken to keep the devices fully saturated; when possible, facilities for occasional flushing should be provided. Finally, any material which may cause development of gas through electrolysis must be avoided.

4.2.6 Gas or air bubbles in soil surrounding the tip

Air or gas bubbles entrapped in the soil or dissolved in water in the vicinity of the filter tip increase the time lag. The changes in volume of the gas and the decrease in soil permeability due to the presence of gas bubbles are responsible for the increased time lag. It is often impossible to control the presence of air or other gas in the soil since this is encountered in natural deposits, even below groundwater level. However, equipments which are not affected by electrolysis should be used in order to avoid the development of gas bubbles which can possibly migrate to the surrounding soil.

4.2.7 Clogging of the filter area

One of the main problems when using piezometers is the clogging of the filter area, which occurs when small soil particles migrate and obstruct partially, and sometimes almost totally, the porous element of the filter tip.

Most of the clogging occurs when the filter tip is pushed or driven into the deposit, but it may also take place during the regular use of the piezometer since water flow from the soil to the tip will create movement of small particles which will gather in the porous element or in the soil surrounding the tip. Open systems are more subject to clogging than closed systems because water movements are much larger in this type of piezometer.

The clogging of the filter area will result in an increase of the time lag, and it may sometimes be of such importance that the piezometer becomes unusable. Open systems should therefore be regularly controlled by filling the pipe or the plastic tube with water and looking at the stabilization process.

4.2.8 Temperature variations

Temperature variations have very different effects, depending on the type of piezometer.

The open standpipe is not affected by day-to-day variations. However, low temperatures may result in changes in the density of the fluid in the upper part of the open line, which must be taken into account in the calculation of the pore pressure in the filter tip. In some cases, the fluid may freeze, making it impossible to use the piezometer; the use of non-freezing fluid is then necessary, but an eventual difference in density must always be considered.

The hydraulic piezometer suffers from small temperature variations since the fluid in the lines is directly influenced by the temperature. Any change in temperature will create a variation in volume of the fluid that will consequently change the pressure indicated on the gauge. The sections of line situated above the ground must be protected against variations in climatic conditions. During the winter, non-freezing fluid must be used for the same reasons as those described for the open standpipe and the same precautions concerning differences in density are applicable.

Measurements performed with electrical or pneumatic piezometers are not directly affected by temperature changes. However, certain problems may occur with the electrical piezometer due to freezing of the electric cables. Air lines used for the pneumatic piezometer may also suffer from cold temperatures, especially if there is a significant amount of condensation inside them. Use of dry gas such as nitrogen is therefore recommended to decrease the condensation problem.

4.2.9 Atmospheric pressure variations

Very little is known about the influence of variations in atmospheric pressure on the pore pressure. Experience has only shown that, when using absolute pressure transducers, a correction for atmospheric pressure must be made to obtain a correct value of the pore pressure.

However, when the atmospheric pressure changes rapidly during the period of measurement it is not absolutely certain that the variations influence instantly the deeper layers of the deposit. For example, if the soil is not fully saturated, the change in air or gas volume will delay transmission of the variation. For any measurement performed during this period, it may be wrong to make the full correction for atmospheric pressure; however, no analysis of this phenomenon has been made and it remains impossible to evaluate its importance.

4.2.10 Movement of the tip

Any movement of the tip results in a disturbance of the pore pressure in the tip and its vicinity. When piezometers are installed on a construction site, they must be protected against movements caused by heavy machinery working in the surroundings.

Measurements of pore pressure performed directly under or in the vicinity of a mass subjected to large settlements, for example under road embankments, may be affected by movements of the tips since the piezometer will tend to follow the soil in which it is installed.

A similar problem will occur if the soil in which the piezometer is installed is affected by frost heave. The piezometer may then follow the movement upwards during freezing and downwards during thawing.

Finally, measurements in a natural slope will also suffer from movements in the soil mass if the area moves as a result of instability.

4.2.11 Instrument errors - Operator errors

Errors in the measurements may be caused by problems with the instrument itself or by incorrect handling by the operator. The precision of the instrument has to be taken into account when the pore pressure is being measured. Finally, evaluation of the pore pressure at the filter level may be erroneous through faulty calibration of the instrument or by inaccurate knowledge of the exact position of the transducer in relation to the filter.

4.3 SPECIAL PROBLEMS WITH LONG-TERM MEASUREMENTS

4.3.1 Disaturation

Long-term use of a piezometer may be affected by disaturation of the system. Facilities for resaturation by flushing should be provided whenever possible. For example, since the presence of air has a serious influence on both the pore pressure values and the time lag of open standpipe and hydraulic piezometers, a second line should be installed in such systems when used for long-term measurements.

Disaturation of a closed system such as the electrical or the pneumatic piezometer creates a more serious problem since it is practically impossible to perform a resaturation. However, the error does not affect the value of the pore pressure but only the time lag. Since the time lag of these systems is very low from the start, this problem is not critical.

4.3.2 Change in calibration characteristics

The electrical piezometer (vibrating wire or resistance strain gauge) may be affected by changes in the calibration characteristics during long-term use. Both the zero-value (value corresponding to a zero pressure) and the calibration constant (number of units corresponding to one unit of pressure) may drift with time. It is very important to be able to check these two values at different intervals. The typical electrical piezometer does not allow any verification of the zero-value and the calibration constant, but the former can be verified on some special piezometers. The use of a removable transducer for measuring the pore pressure in the BAT filter tips makes these verifications easy to perform.

4.3.3 Chemical reactions

Problems due to chemical reactions with the pore water may occur in any system used for long-term measurement of pore pressure. These problems will mostly affect the measuring systems containing moving parts, e.g. electrical, pneumatic or BAT piezometers. Corrosion or deposition of reaction products around these elements will obstruct or damage the measuring system. In order to diminish these problems, specially treated material such as galvanic pipes should be used in the installation, and only piezometers fabricated with non-corrosive material such as stainless steel should be installed.

5. *EXPERIENCE FROM PREVIOUS PROJECTS*

5.1 INTRODUCTION

Before presenting the results from the two test sites studied in this project (Linköping and Munkedal), the pore pressure measurements in two earlier projects (Örebro and Skå Edeby) will be discussed in the present chapter. Even though the measurements were not specifically performed for studying the behaviour of the piezometers, they are nevertheless interesting for the present study since the general conclusions which can be drawn from a new interpretation and a closer examination of the results may be useful.

5.2 MEASUREMENTS AT ÖREBRO

During the construction of road E3, south-west of the city of Örebro (about 200 km west of Stockholm), a study of different types of vertical drainage system was undertaken, for which a soil investigation was performed (Eriksson and Ekström 1983). The soil in this area consists of about 4 m of soft homogeneous post-glacial clay underlaid by a layer of 4 m of soft varved glacial clay. Both the glacial and the post-glacial clays are slightly overconsolidated. The undrained shear strength evaluated by Swedish fall-cone tests is between 8 and 10 kPa and the sensitivity was found to be between 5 and 80. The water content is between 90 and 100% and is about the same as the liquid limit.

As part of this study, a number of piezometers were installed at two different levels in order to follow the fluctuations and the dissipation of the pore pressure during and after the construction of the road. Four types of piezometer were used, two open systems (type Geotech) and two closed systems (type NGI and an older version of type BAT). Figures 27 and 28 show the measurements performed between October 1978 and September 1985 at these two levels. It can be seen from these measurements that until October 1982 the four types of piezometers were performing satisfactorily and gave values in fairly good agreement with each other. However, after this period, the NGI piezometers started to show instability and finally ceased to work in October 1982 (Figure 27) and September 1983 (Figure 28) respectively. The open standpipe piezometers have, up to now, worked satisfactorily, despite problems due to the presence of air/gas in the tips which had to be de-aired on one occasion (Eskilsson 1986), and also due to water freezing during the winter period. No measurements have been made with the BAT piezometers since the end of 1982.

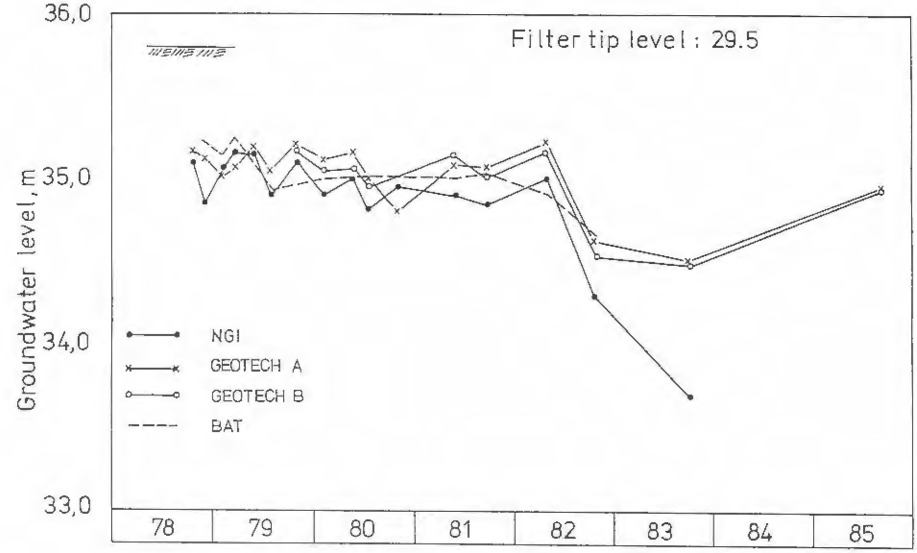


Fig. 27. Pore pressure measurements at Örebro - level 29.5.

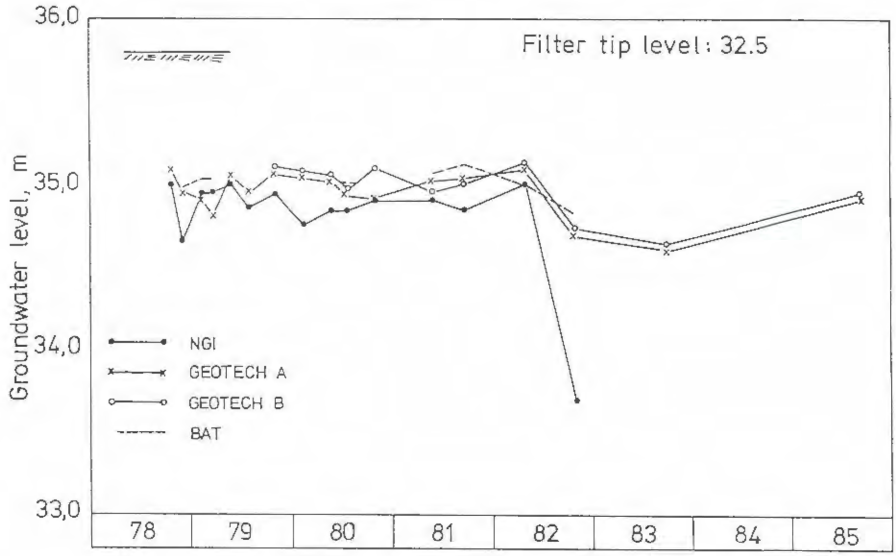


Fig. 28. Pore pressure measurements at Örebro - level 32.5.

In summary, it appears that the four types of piezometer have given excellent results during the first four years of measurement of the pore pressure variations. After that period, only the open system could be relied on.

5.3 MEASUREMENT AT SKÅ-EDEBY

The Skå-Edeby test field, located about 25 km west of Stockholm, was built in 1957 by the Swedish Geotechnical Institute (Hansbo 1960, Holtz and Broms 1972). It consists of four circular test fills as shown in Figure 29. The pore pressure measurements discussed here have been recorded under the test fill build in Area IV. The soil consists of an upper layer of 3 m of soft post-glacial clay which is slightly organic, beneath which is 9 m of soft to medium soft varved glacial clay. The shear strength is between 10 and 25 kPa and the sensitivity is between 5 and 10. The water content decreases from 80% in the upper part of the deposit to 60% at a depth of 12 m. The groundwater table was usually located between 0.5 m and 1.0 m under the ground surface.

In the present section, the measurements from seven piezometers installed at different depths will be discussed. The electrical resistance strain gauge piezometers are equipped with an open tube used for the transmission of the atmospheric pressure behind the membrane of the transducer. This tube keeps the transducer in contact with the air pressure at ground level and the measurements should therefore not be affected by changes in atmospheric pressure.

The measurements performed over a period of more than 50 days are presented in Figure 30. Two short periods of measurement are specially interesting because of the unusual response of the piezometers to the variations in atmospheric pressure.

During the first period (Figure 31), piezometer K3 reacted strangely, showing a significant increase of the pore pressure on January 24, corresponding to a decrease in the atmospheric pressure. Similar observations were made again a few days later (January 26-27). In view of the stable values measured in the other piezometers, it seems that piezometer K3 was already at this stage affected in some way by the atmospheric pressure.

These irregularities have become even more evident during the second period presented in Figure 32. During this period, all the piezometers have been directly affected, to different degrees, by changes in the atmospheric pressure. The pressures measured by the piezometers showed variations closely following the changes in air pressure.

The measurements performed during these two periods at Skå-Edeby showed that the piezometers, even though they were made for measuring the relative pressure, were in some circumstances affected by the variations in the atmospheric pressure. This may be explained by the fact that the small tube used for transmitting the atmospheric pressure to the transducer was damaged or obstructed by the presence of dirt or condensation water in the tube.

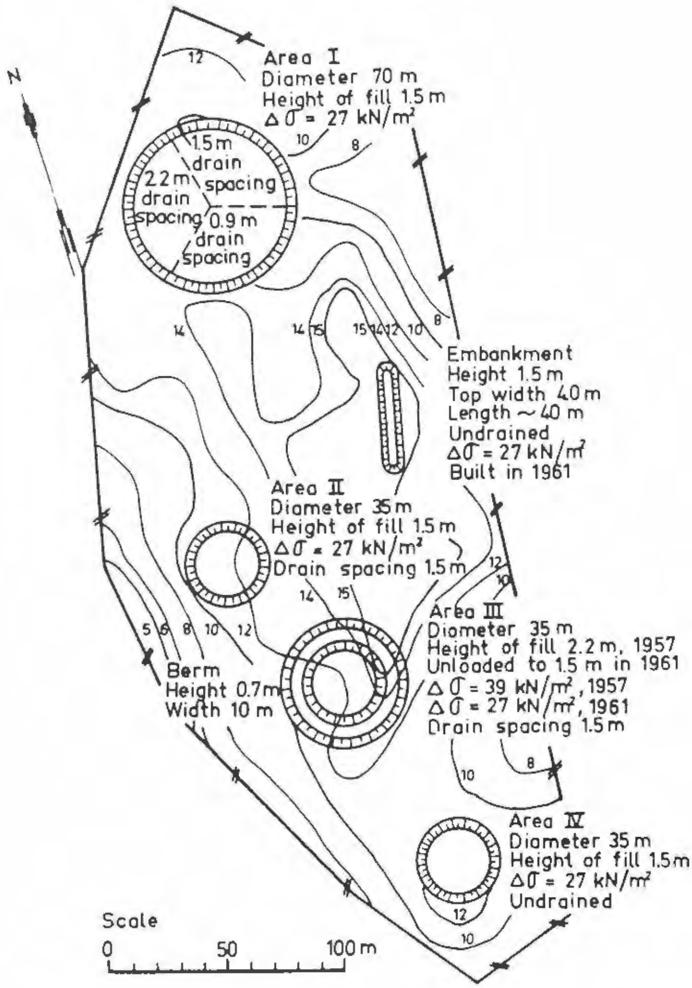


Fig. 29. Localization of the test embankments at Skå-Edeby (Holtz and Broms 1972).

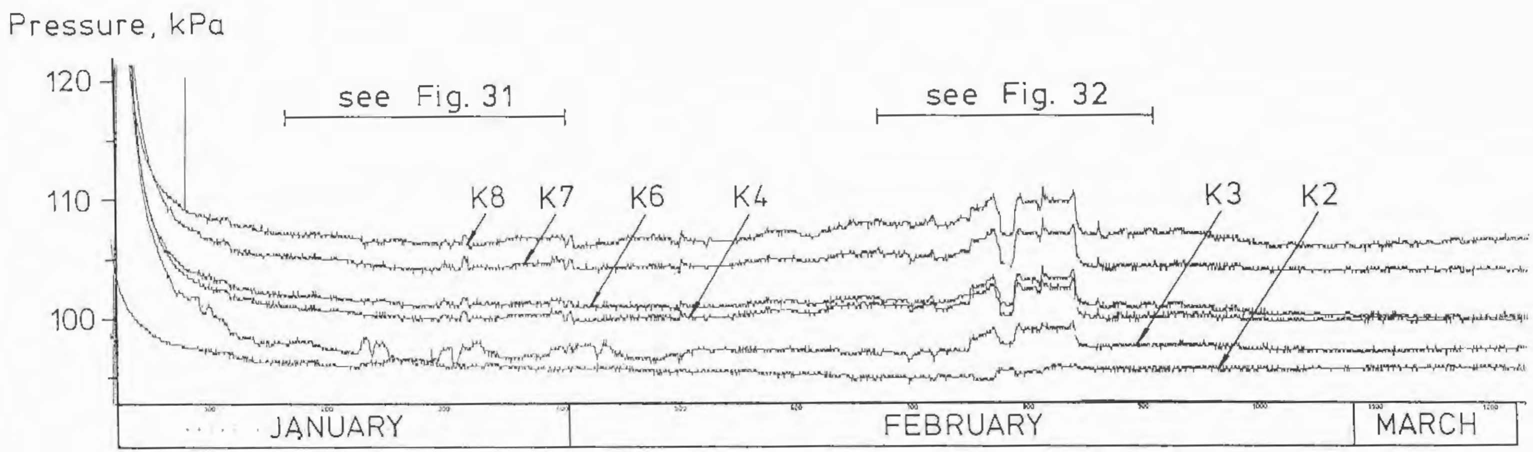


Fig. 30. Pore pressure measurements at Skå-Edeby.

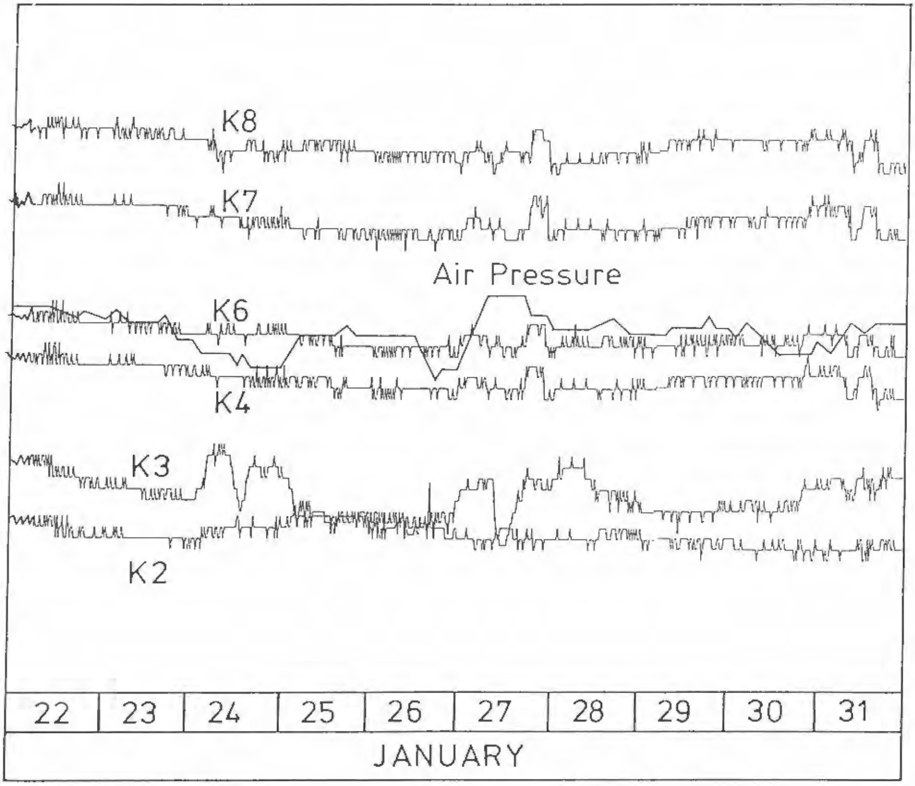


Fig. 31. Pore pressure measurements at Skå-Edeby (see Fig. 30).

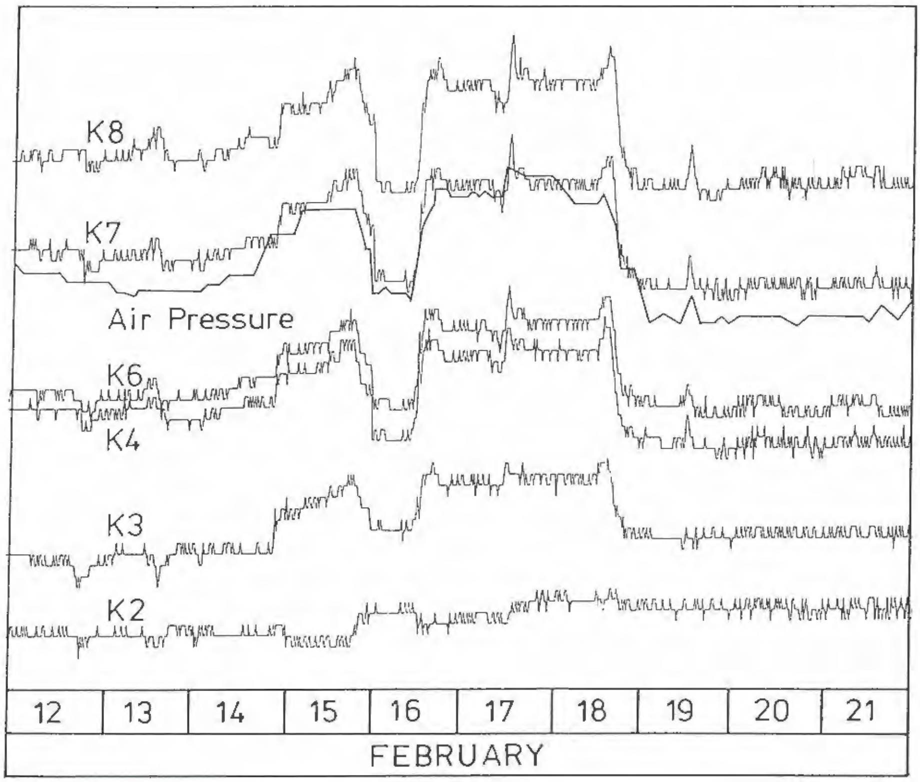


Fig. 32. Pore pressure measurements at Skå-Edeby (see Fig. 30).

5.4 CONCLUSIONS

The two projects have produced interesting results regarding the measurements of pore pressure. At Örebro, the use of four different systems showed that all of them could be used with satisfaction for measuring the normal variations in pore pressure, but that some piezometers became defective after a certain period and therefore had to be replaced.

The measurements at Skå-Edeby revealed a very important problem when using relative pressure transducers. The measurements showed that the small tube used for adjustment of the measuring system to the air pressure may be obstructed or damaged during the period of measurement. In such a case, the transducer becomes affected by variations in the atmospheric pressure which may be registered by the piezometer and identified incorrectly as variations in the pore pressure.

6. PORE PRESSURE MEASUREMENTS AT LINKÖPING

6.1 PURPOSE OF THE INVESTIGATION

6.1.1 Comparison of different systems

Since the main purpose of the project is to measure reliably the variations in pore pressure under normal conditions, it was important to acquire a better knowledge of the ability of different piezometers to measure natural variations in pore pressure. Hence, the primary purpose of the investigation at Linköping was to study the behaviour of different types of piezometers.

The instruments chosen for the investigation are based on different basic measuring principles and the study concentrated mainly on the precision and the response time of the piezometers.

6.1.2 Influence of the atmospheric pressure

The second purpose of this investigation is to analyse the influence of the variations in the atmospheric pressure on the pore pressure measurements.

Absolute pressure transducers are often used for measuring pore pressure without any attention to the atmospheric pressure during the measurement. The pore pressure value is taken directly from a calibration curve, which is used as if the atmospheric pressure had no influence.

In fact, the pressure registered by the absolute pressure transducer is the sum of the pore pressure at the filter level and the atmospheric pressure transmitted to this level during measurement. The pore pressure can then be evaluated by using a calibration curve, which may be presented in two different ways, Figure 33.

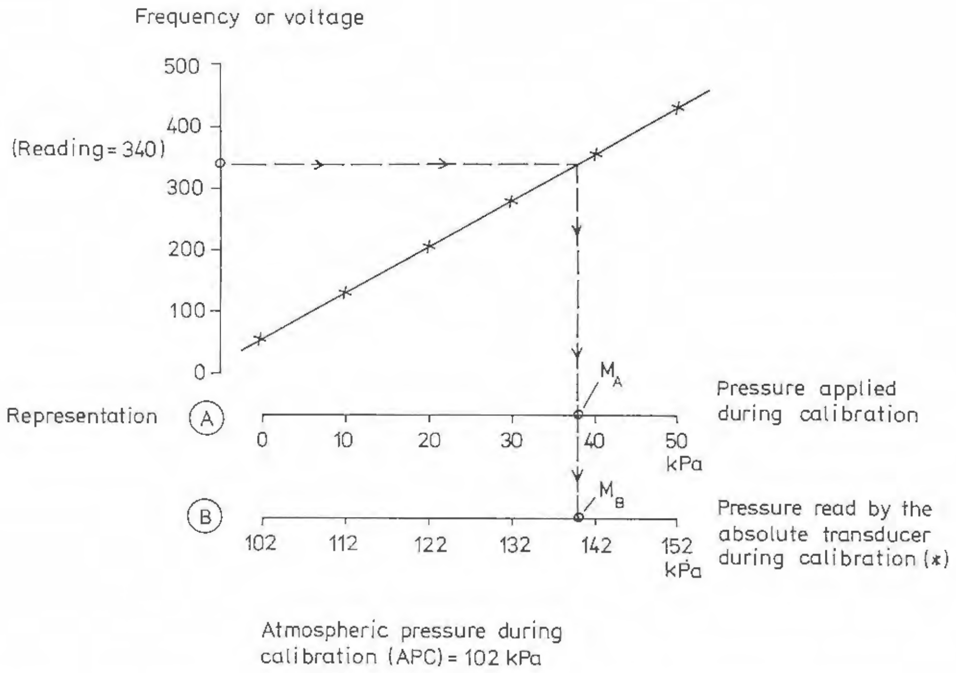


Fig. 33. Different representation methods of the calibration curve.

If representation "A" is used (pressure from 0 to 50 kPa), the atmospheric pressure during calibration must be noted and the pore pressure is evaluated from the equation:

$$u = M_A + APC - APM \qquad (2)$$

where u = pore pressure during measurement
M_A = pressure read on scale "A", (see Figure 33)
APC = atmospheric pressure during calibration
APM = atmospheric pressure during measurement

In representation "B", the atmospheric pressure is immediately added to the pressure applied during calibration and the following equation is used for calculating the pore pressure:

$$u = M_B - APM \qquad (3)$$

where M_B = pressure read on scale "B", (see Figure 33).

However, in common practice, the atmospheric pressure is seldom measured at a site and is therefore not taken into account when evaluating the pore pressure with absolute transducers. The first representation of the calibration curve is then used without any further consideration to the atmospheric pressure during calibration or measurement.

6.2 SITE CONDITIONS

The city of Linköping is situated about 200 km south-west of Stockholm. The site chosen for the investigation is located along motorway E4, about 1 km north of the city. The site is used for waste disposal and has therefore been the object of previous field investigations (Hydén 1984), which had to be completed in the installation area.

The stratigraphy of the site was studied by performing cone penetration tests and pore pressure soundings. The upper 1-2 m are formed of fill material from the surrounding area. Beneath this fill material is a dry clay crust (2-3 m) covering a clay deposit consisting of two different layers of post-glacial clay (5-11 m and 11-14 m) and a layer of glacial clay (below 14 m).

6.3 DESCRIPTION OF THE INSTRUMENTS

6.3.1 Open standpipe piezometers

Three open standpipe piezometers have been installed at Linköping. Two of them are of the Geotech type and can be described as perforated pipes filled with a mixture of sand and epoxy. The main differences between the two tips, which may be seen in Figures 34a and 34b, concern the length of the tip, the area of the holes (filter area), and the diameter of the open tube. The Geotech piezometers are installed using rods ø25 mm, which can be removed immediately after the installation, while the filter tip remains permanently in the soil together with a one-meter pipe used to prevent water in the hole from reaching the filter area.

The third open standpipe piezometer is formed of a plastic tip with a ceramic filter, Figure 35. It is installed using water pipes (ø1 inch) and can be removed and used several times.

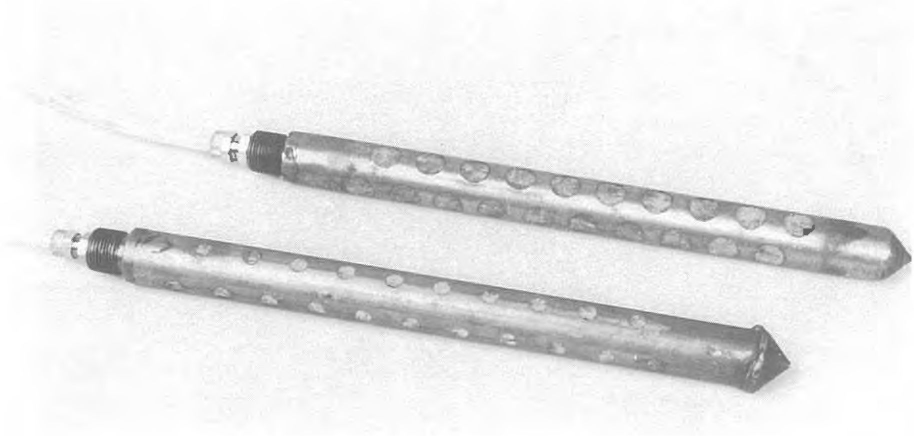


Fig. 34. Open standpipe piezometer of type Geotech.

To read the open standpipe piezometers, a coaxial cable connected to an electrical indicator (voltmeter or other signal) is lowered in the open tube, Figure 36. When the cable end reaches the water surface, the electrical circuit is completed and the contact can be seen on the indicator. The water level can be evaluated by measuring the length of the coaxial cable inside the tube when the contact is registered.

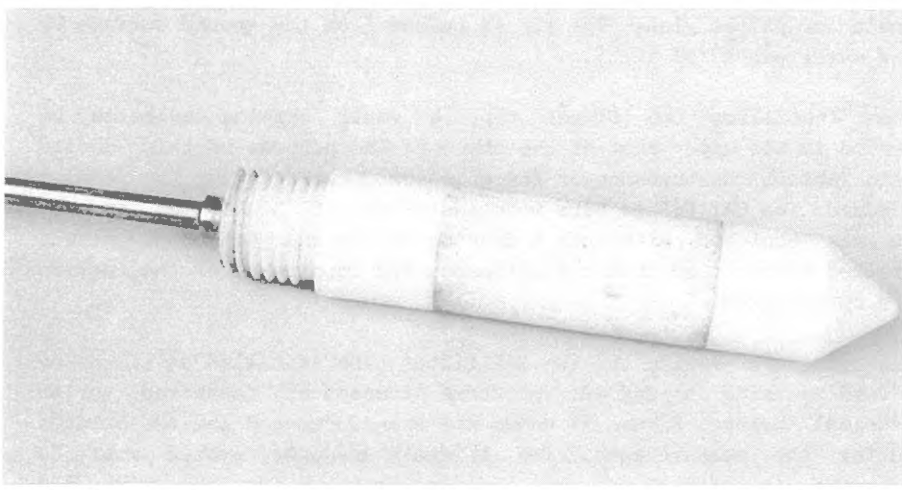


Fig. 35. Open standpipe piezometer with ceramic filter element.

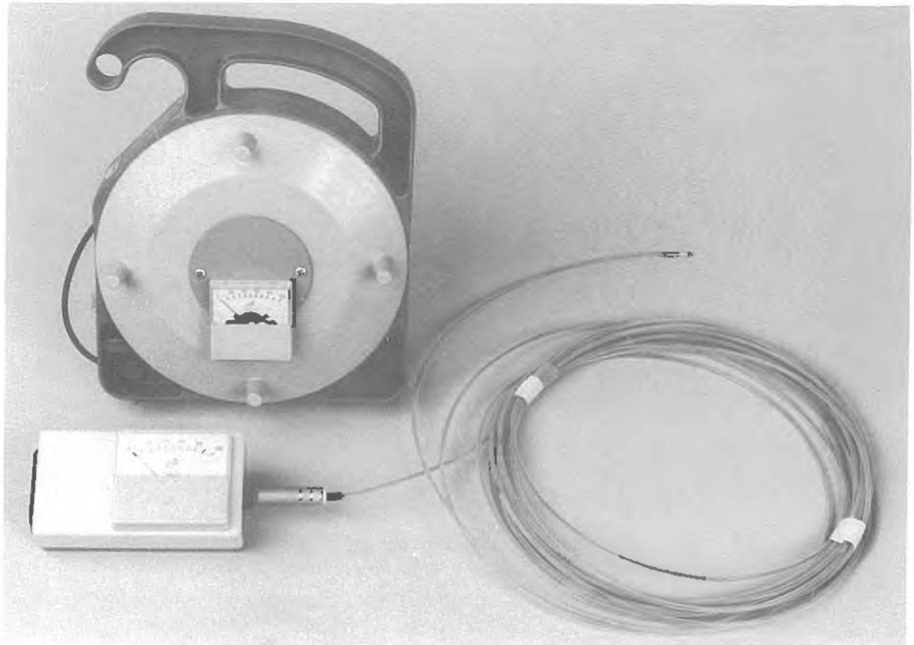


Fig. 36. Reading instruments for open systems.

6.3.2 BAT piezometers

The BAT piezometer is formed of a special closed filter tip presented in Section 3.4.5. (see also Figure 25). The porous element is made of ceramic or polyethylene. The tip is pushed from the ground surface by using water pipes (ø1 inch).

When installing the filter tip, a small damping device may be inserted in the upper part of the chamber. The purpose of this device is to "absorb" disturbance of the pressure created during the reading procedure. Two BAT filter tips were installed at Linköping; one of them was equipped with such a damping device and the second one was installed without, so that the influence and importance of the device could be analysed.

The pressure inside the two BAT filter tips installed at Linköping was read by using a regular pressure transducer connected to an electrical bridge. Figure 37 shows the transducer and the two bridges used for the measurements. The bridge-transducer system must be calibrated in order to evaluate the pore pressure from the value read on the instrument.

Fig. 37. BAT piezometer with reading instruments.

6.3.3 Vibrating wire piezometers

Three vibrating wire piezometers were used in the present study. The first piezometer, made by Geotech, is an absolute pressure piezometer which means that no correction for changes in the atmospheric pressure is made by the transducer. The tip, which is pushed into the deposit using rods ø32 mm is shown in Figure 38 together with the reading instrument.

The two other vibrating wire piezometers are made by Geonor, Figure 39. Both piezometers measure the relative pressure and one of them is provided with a facility for controlling the zero-value during the period of measurement. They were installed in the same way as the Geotech piezometer.

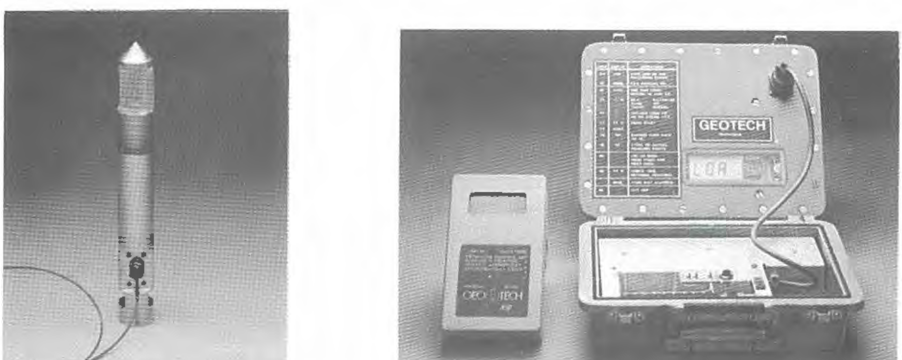


Fig. 38. Vibrating wire piezometer of type Geotech with reading instrument (from GEOTECH, 1980).

Fig. 39. Vibrating wire piezometer of type Geonor with reading instrument.

6.3.4 Resistance strain gauge piezometers

The last four piezometers used in the investigation are electrical resistance strain gauge piezometers. The first one consists of a pressure transducer installed permanently in a Geonor filter tip, Figure 40a. The three others consist of different types of pressure transducers connected to regular BAT filter tips, Figure 40b.

The resistance strain gauge piezometers were connected to an automatic reading and recording system of type Cristie CD12, Figure 41. The CD12 data logger can record information from a maximum of 12 sensors on a digital cassette for subsequent computer analysis. Only analogue inputs are accepted by the system. Each input can be set to one of three selected ranges by means of switches located on the analogue sensor printed circuit board. The system makes it possible to record the date and time on the cassette prior to recording the input data. A small digital display is also located on the panel, allowing the operator to check the data being recorded. The reading and recording system is powered by external batteries which have to be recharged every 3-4 weeks. A battery level indicator is provided on the panel for an instantaneous check on the state of the batteries.

A fifth pressure transducer was connected to the reading and recording system. The transducer was left open at the ground surface for measuring the variations in atmospheric pressure.

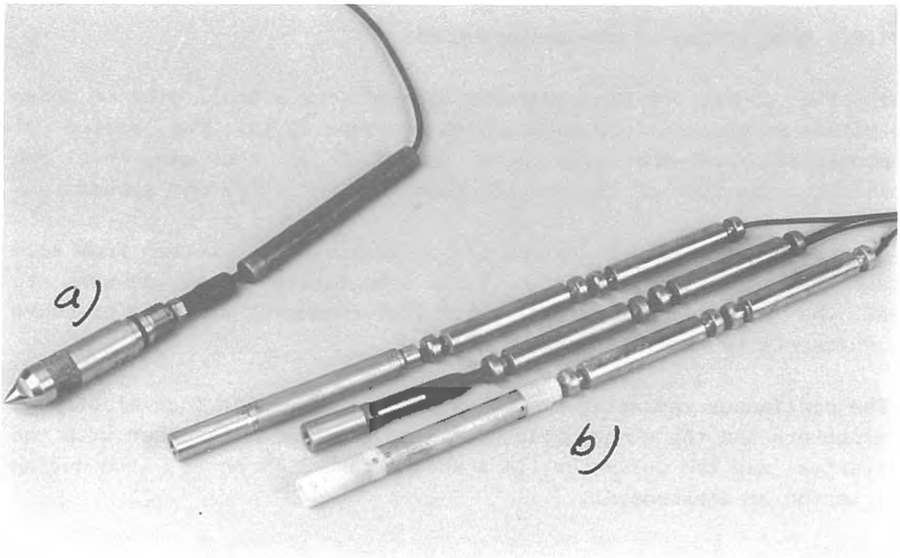


Fig. 40. Resistance strain gauge piezometer for permanent installation or installation on BAT filter tip.

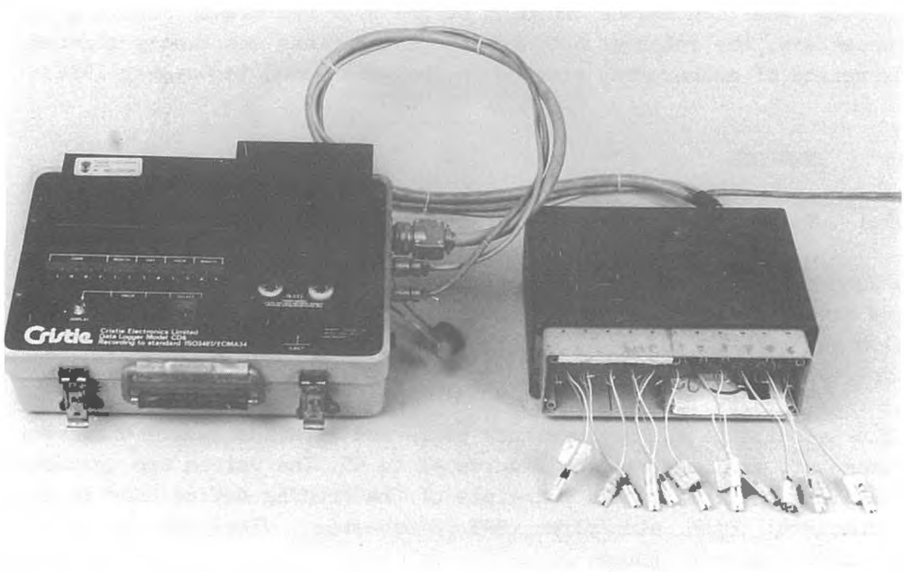


Fig. 41. Automatic reading and recording system.

6.4 INSTALLATION AND MEASUREMENT

6.4.1 Description of the installation

The site chosen for the study was located near a small dike in order to obtain some variations in the pore pressure during the period of measurement. All the tips were installed at the same level for possible comparison of the results obtained from different systems.

The piezometers were installed at a distance of two metres from each other. After installation of the tips, a bentonite slurry was used to seal the prebored holes to avoid disturbance of the pore pressure measurements by the infiltration of water.

The continuous recording system used for reading the four electrical piezometers and the atmospheric pressure was placed, together with the batteries and the voltmeter, in a wooden case left on the site during the period of measurement.

6.4.2 Frequency of measurement

The three open standpipes, the two BAT tips and the three vibrating wire piezometers were read manually once or twice a week between July 1984 and February 1985.

During the continuous reading of the four resistance strain gauge piezometers, the interval between the measurements was twenty minutes. The period of measurement started in July and ended in October 1984.

6.5 RESULTS

6.5.1 Measurement of natural variations in pore pressure

In order to be able to compare the results, all the measurements of pore pressure are compiled and presented as a groundwater level for which a reference has been chosen arbitrarily on the site (ground level = 100 m).

The results of the measurements performed with the twelve different piezometers are presented in Figures 42 to 45. The values are grouped according to the basic principle of the reading device used in the piezometers: open standpipe, BAT piezometer, vibrating wire and resistance strain gauge.

The values obtained from the BAT system do not show any significant differences between the piezometers A and B installed respectively with and without damping device, Figure 43.

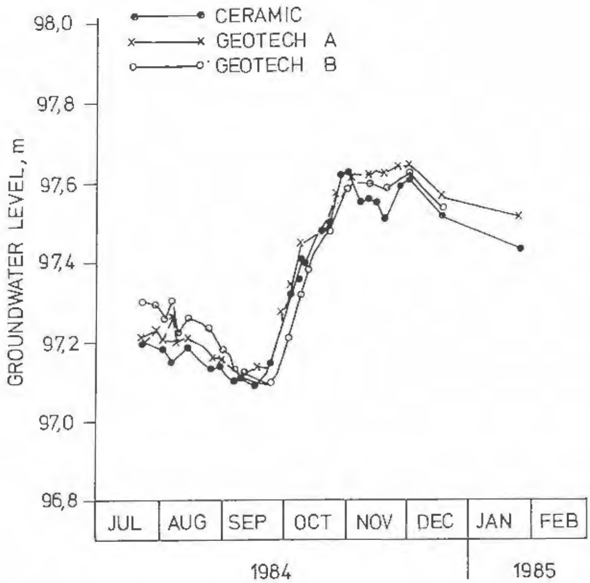


Fig. 42. Pore pressure measurements at Linköping - open standpipe piezometers.

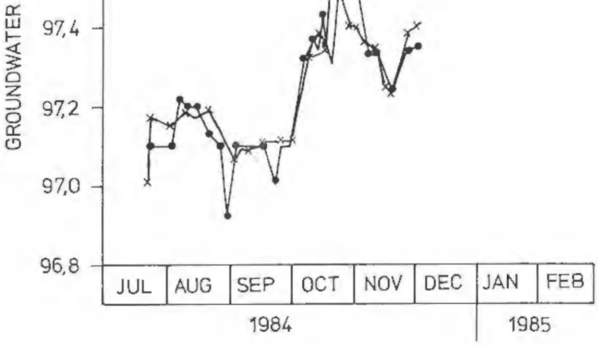


Fig. 43. Pore pressure measurements at Linköping - BAT piezometers.

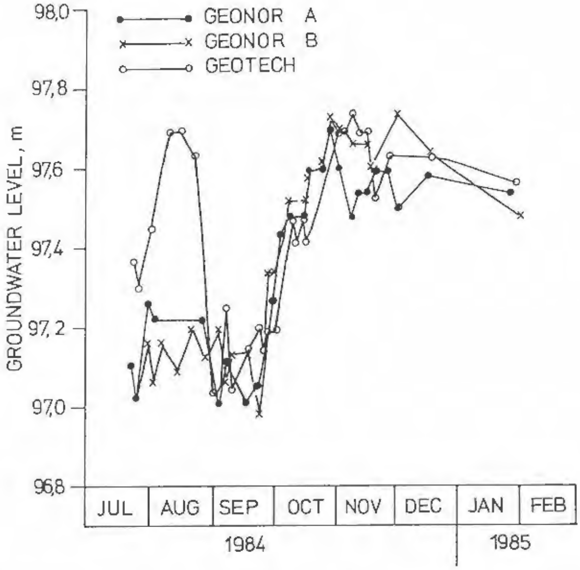


Fig. 44. Pore pressure measurements at Linköping - vibrating wire piezometers.

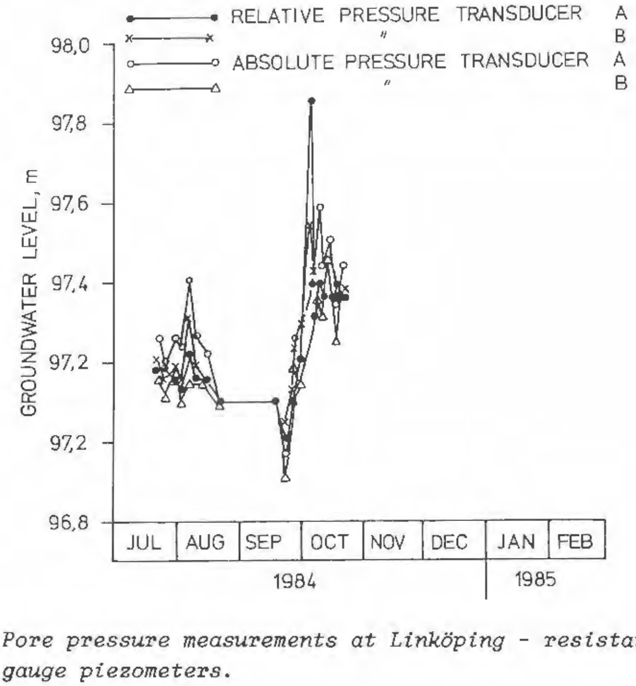


Fig. 45. Pore pressure measurements at Linköping - resistance strain gauge piezometers.

The Figure 44 indicates some problems at the beginning of the period of measurement with the piezometer Geotech; these problems were due to a bad connection with the reading instrument and was solved for the measurements performed after September 1984. The important scattering is due to the poor precision of the reading system used (0,5 kPa). The values read manually on the four electrical resistance strain gauge piezometers (Fig. 45) also show some scattering for the same reason as above. However, the measurements performed with the three open standpipe piezometers (Fig. 42) show a small scattering and a smooth configuration due to the long response time of this type of system.

In order to eliminate the scattering due to the different accuracy of the reading instruments, the average values of each group was calculated. The comparison of all the results compiled in Figure 46 shows that the measurements from the different types of piezometer are fairly similar and that all of these systems may be used for registration of natural variations in the pore pressure, provided that the accuracy of the reading instrument is satisfactory.

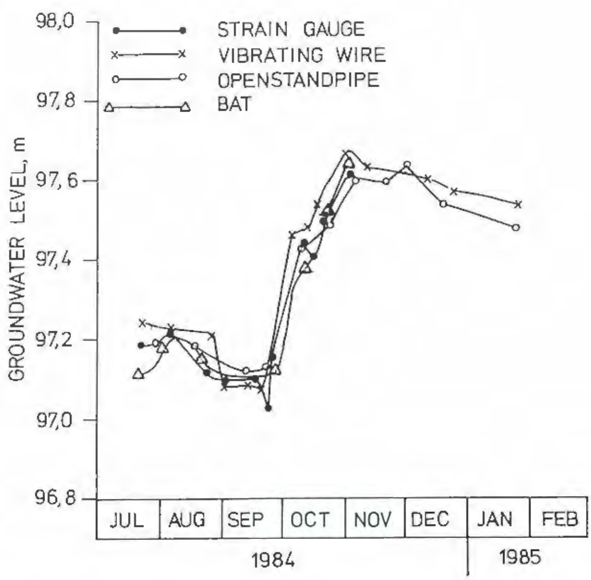


Fig. 46. Pore pressure measurements at Linköping - comparison of the four groups of piezometers.

..5.2 Influence of atmospheric pressure on the measurements

In order to study the influence of the atmospheric pressure on the pore pressure measurements, the automatic reading and recording system was used. Two of the piezometers were equipped with absolute pressure transducers, while the other two had relative pressure transducers. As explained before, one reading of the pore pressure was taken every twenty minutes together with the atmospheric pressure and the temperature.

Figures 47 and 48 present the measurements performed during two different periods of summer and autumn 1984. The atmospheric pressure is shown in Figures 47a and 48a. The pore pressure measurements performed with the relative pressure transducers are given in Figures 47b and 48b.

In order to demonstrate the influence of variations in atmospheric pressure, the measurements performed with the absolute pressure transducers are first presented without taking into account the atmospheric pressure during the calibration or during the period of measurement, Figures 47c and 48c. The variations in pore pressure analysed in this way seem to be much more important than the variations registered by the relative pressure transducers. However, after correction for the variations in atmospheric pressure, the measurements performed with absolute pressure transducers become representative for the actual pore pressure variations, Figures 47d and 48d.

The comparison between the values obtained from relative pressure transducers (Figure 47b and 48b) and absolute pressure transducers after correction (Figure 47d and 48d) shows good agreement. However, comparison with the non-corrected measurements performed with the absolute pressure transducers (Figures 47c and 48c) clearly indicates that the influence of atmospheric pressure on measurements performed with absolute pressure transducers is not negligible and has to be taken into account in the interpretation of the results.

However, it is still uncertain to which extend this correction should be made for piezometers installed at different depths. The influence of the atmospheric pressure may decrease, or at least be delayed, in deeper soil layers. In this case, the magnitude of the correction should be related to the depth of installation and the characteristics of the system soil/water. Unfortunately, this influence with depth is still unknown, therefore the full correction should be made until further research clarifies this problem.

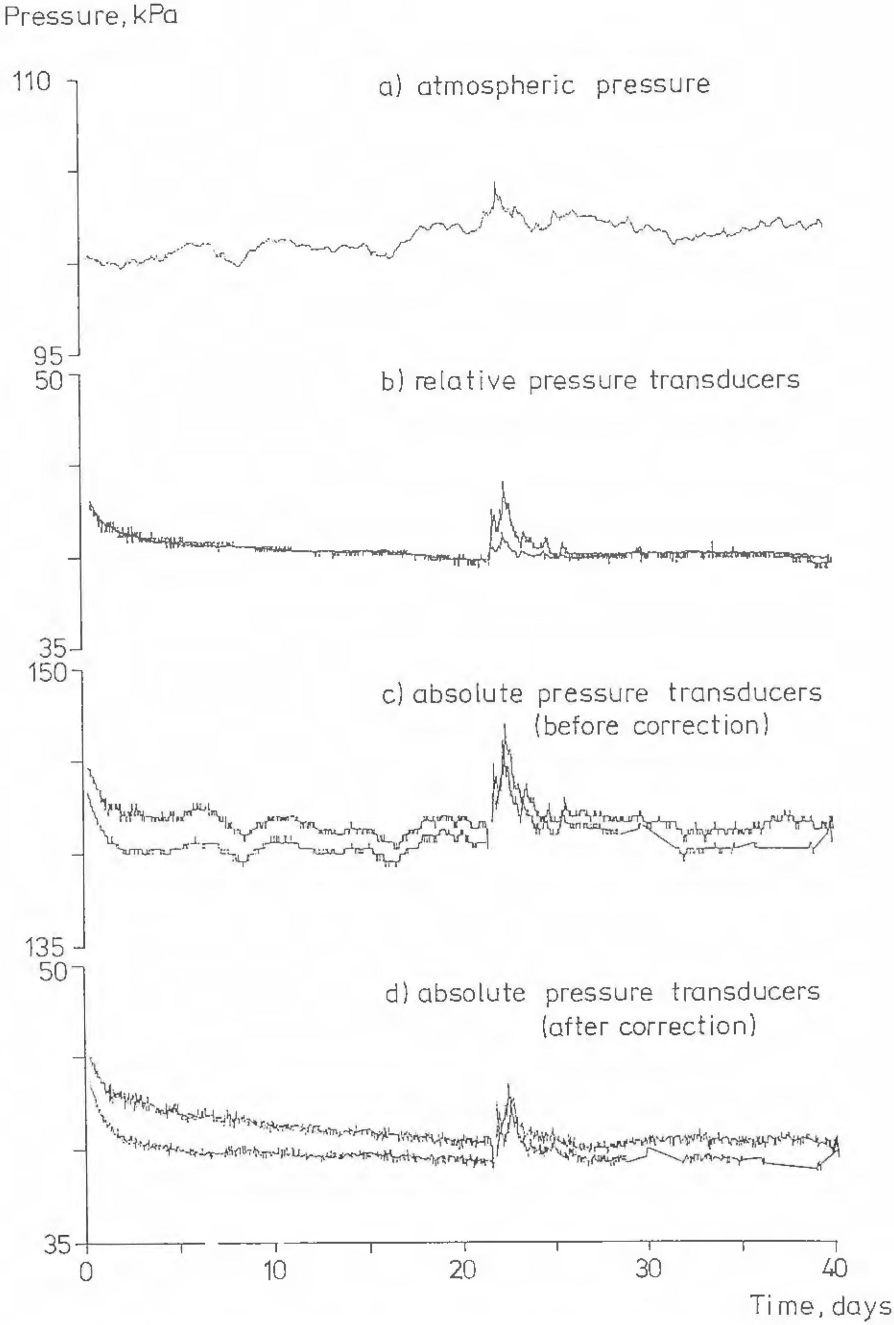


Fig. 47. Pore pressure and atmospheric pressure measurements at Linköping - Jul/Aug 1984.

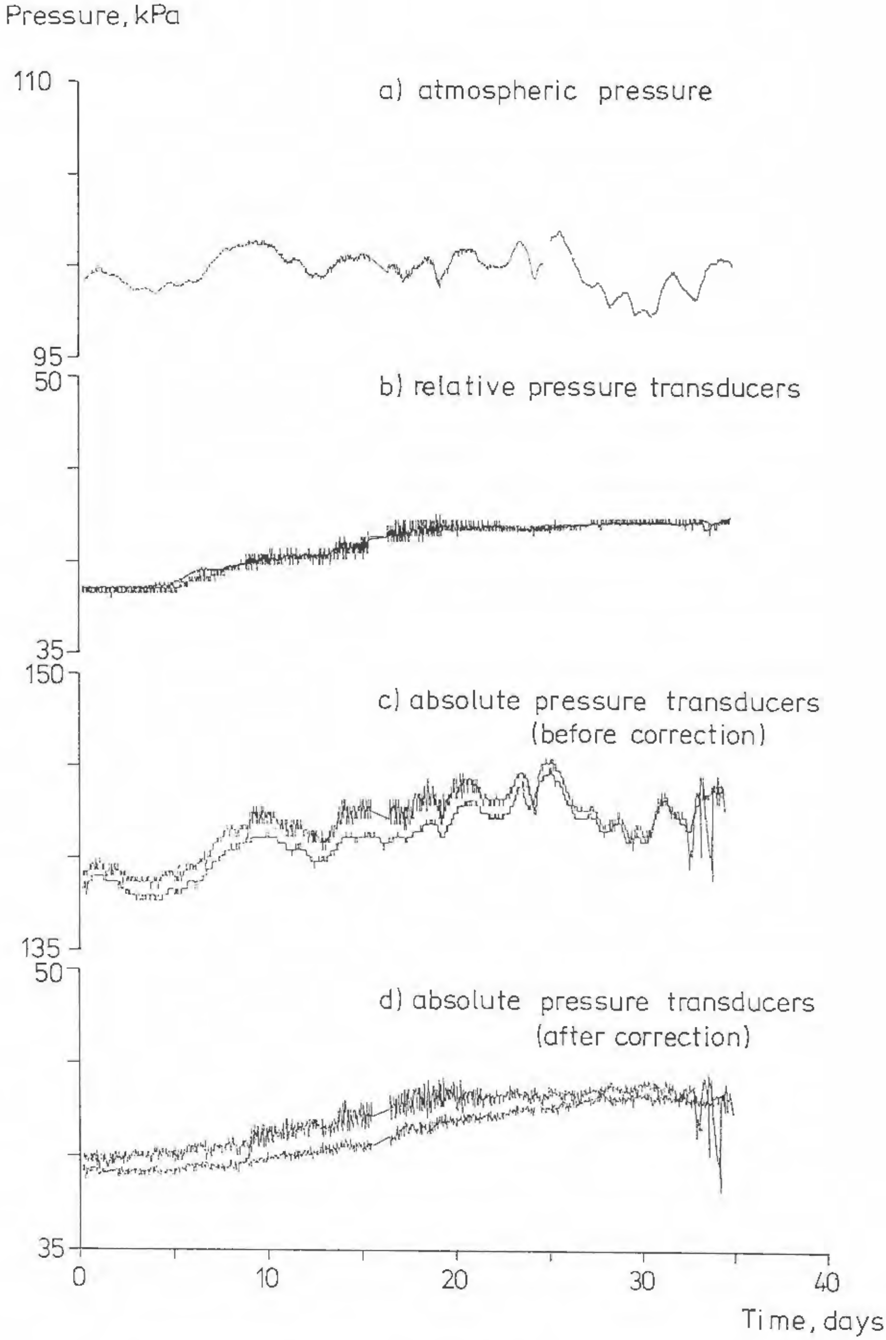


Fig. 48 Pore pressure and atmospheric pressure measurements at Linköping - Sep/Oct 1984.

7. PORE PRESSURE MEASUREMENTS AT MUNKEDAL

7.1 PURPOSE OF THE INVESTIGATION

As mentioned in the introduction, the pore pressure is one of the parameters which can be analysed and used in a warning system for slope stability.

The present study was performed to investigate the possibility of measuring pore pressure over a long period of time and to study certain potential problems such as the stability and reliability of the recording system, the long-term behaviour of the piezometers and problems of interpretation.

The main purpose of this study was to determine the fundamental characteristics of the piezometers and the measuring system which are necessary for long-term measurement and continuous recording of pore pressures.

7.2 SITE CONDITIONS

The locality of Munkedal, situated about 100 km north of Gothenburg on the Swedish west coast, is crossed by the Örekil river, which has eroded the deep clay layers deposited in this area. The difference in elevation between the crest of the slope and the river is about 20 m. The soil consists of about 40 m of very soft to medium soft quick clay with an undrained shear strength of about 20 kPa at the top of the slope increasing to 105 kPa near the firm bottom layers. The water content is between 26 and 68% and the liquid limit is between 28 and 56%. The sensitivity was found to be up to 350.

The area has been subject to several landslides in the past. The investigated area is located between two earlier slides which occurred in 1895 (northern part) and 1940 (southern part) as shown in Figure 49. The first stability analysis using total stresses indicated that the most dangerous area was located in sections B and C as shown in Figure 49. The safety factor calculated for slip sufaces in section C was between 0.9 and 1.1, Figure 50. Because of the risk of new slides occuring in the area and the danger of such a slide for the population of Munkedal, various corrective measures were taken in order to stabilize the slope. These measures included the moving of the Örekil river and the construction of a pressure berm at the toe of the slope, Figures 49 and 50.

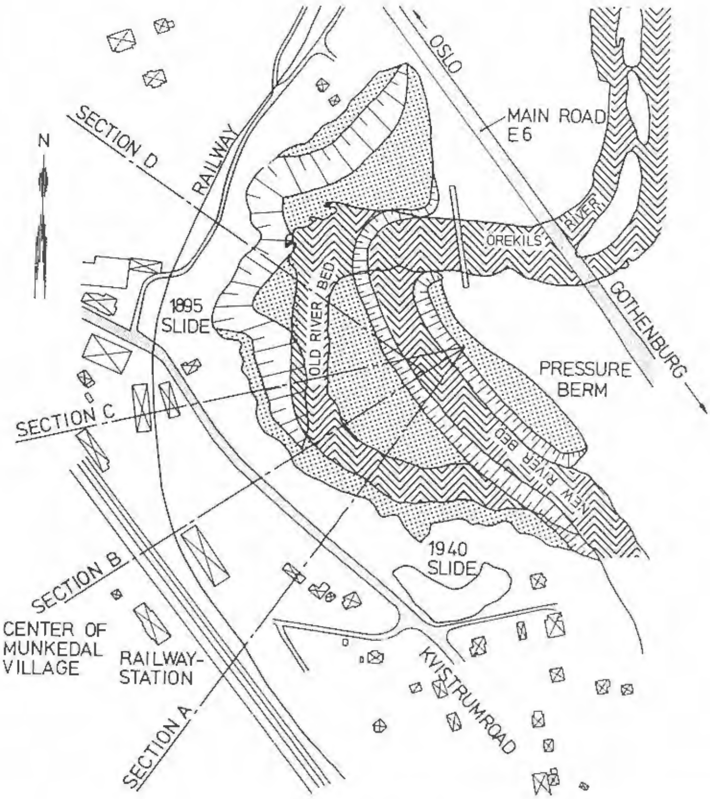


Fig. 49. Plan of investigated area and stabilization measures, Munkedal.

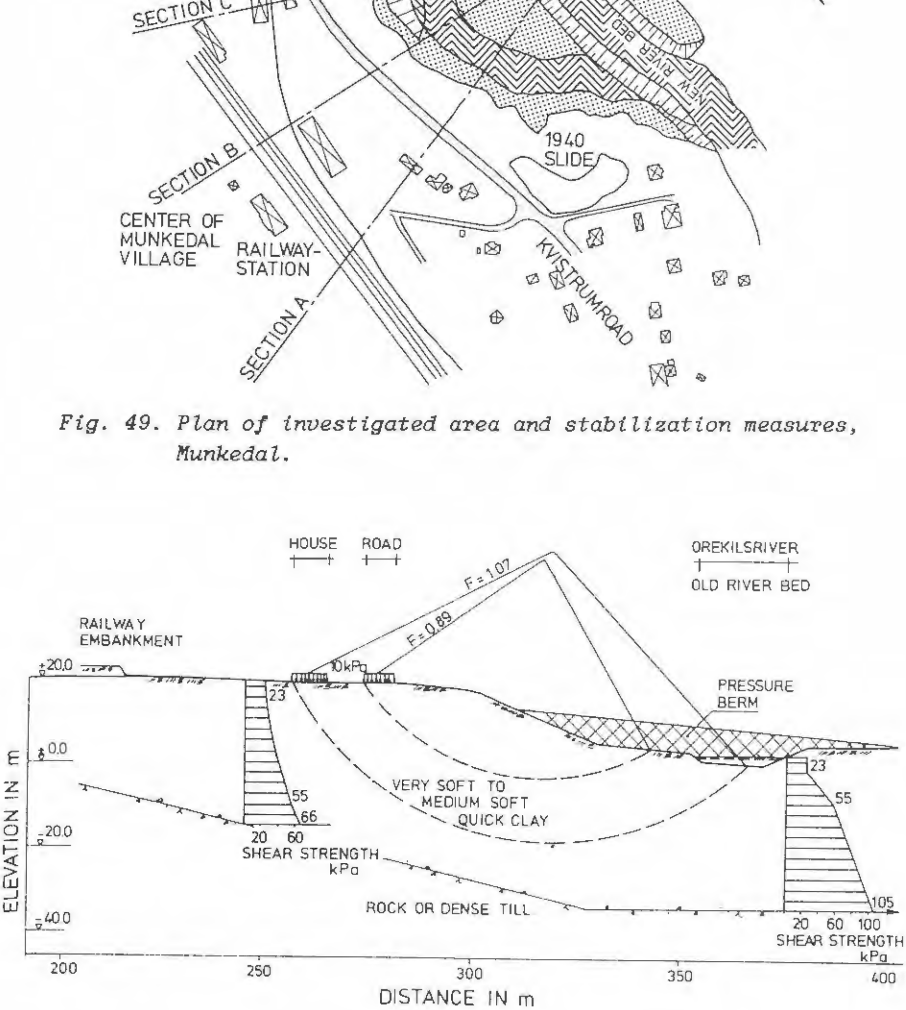


Fig. 50. Section C of the clay slope with calculated most dangerous slip surfaces and stabilizing pressure berm, Munkedal.

7.3 CHOICE OF THE INSTALLATION DEPTHS

Three sections were instrumented to obtain the pore pressure distribution in the slope; these are located respectively at the toe, at the crest and some distance behind the slope (sections 1, 2 and 3). The depths of installation of the filter tips in sections 1 and 2 were chosen so that the piezometers would be located in the most critical zone according to the slope stability analysis. For section 3, the depths of installation were selected to find the pore pressure in the middle of the clay layer outside the shear zone, and in the botton layer looking for a possible influence of the surrounding mountains. This section was to be used as a reference section for the interpretation of the measurements. Figure 51 presents the exact location and depth of the piezometers installed.

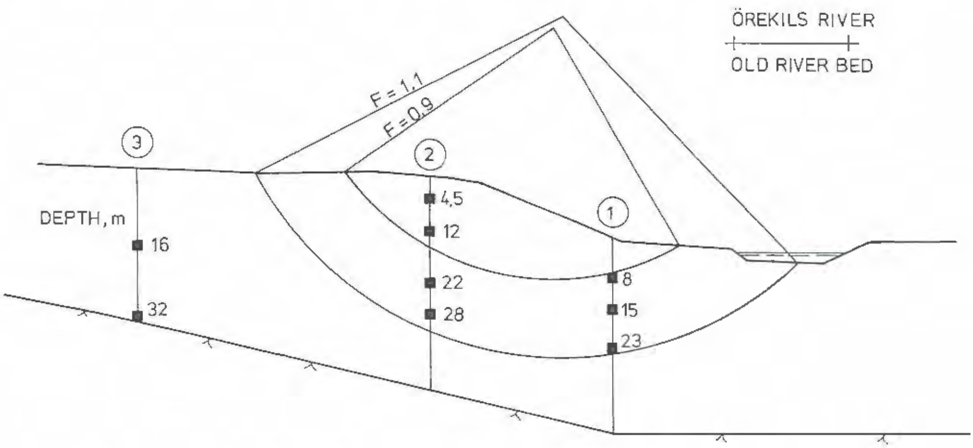


Fig. 51. Sections for pore pressure measurements with depth of installation of the piezometers, Munkedal.

7.4 PRESENTATION OF THE SYSTEM

The system installed at Munkedal for measuring pore pressures is formed of BAT filter tips, resistance strain gauge transducers (type SGI), and an automatic reading and recording system.

The BAT filter tip (see Sections 3.4.5 and 6.3.2) was chosen partly because of its short response time (short time lag) for the transmission of the pore pressure variations. However, the most important characteristic of this type of filter tip is the possibility of using a removable transducer, which enables calibration during the period of measurement or replacement of defective transducers. The filter tips were pushed from the ground surface into the deposit to the selected depths.

The pressure transducers used in the system are fabricated at SGI using electrical resistance strain gauges. The range of utilization of the transducers is variable (0-200, 0-300 or 0-400 kPa) and the accuracy also varies according to the maximal acceptable pressure (0.2, 0.3 or 0.4 kPa). The transducers are absolute transducers, i.e. any variation in atmospheric pressure which influences the pore pressure at the installation level is recorded by the instruments.

The continuous reading and recording system installed at Munkedal used the same equipment as that at Linköping (see Section 6.3.5). The equipment was placed in a wooden case during the first months and was moved to an insulated housing in January 1985, where it was protected against severe winter weather conditions.

The pore pressure measured by ten piezometers, the atmospheric pressure and the temperature were recorded every twenty minutes from November 1984 to December 1985, and thereafter every one hour until March 1986.

7.5 PRESENTATION OF THE RESULTS

Owing to the large number of measurements performed at Munkedal between November 1984 and March 1986, it is impossible for this report to present all the values recorded. However, Figures 52, 53 and 54 present the fluctuations in pore pressures at sections 1, 2 and 3 respectively during this period.

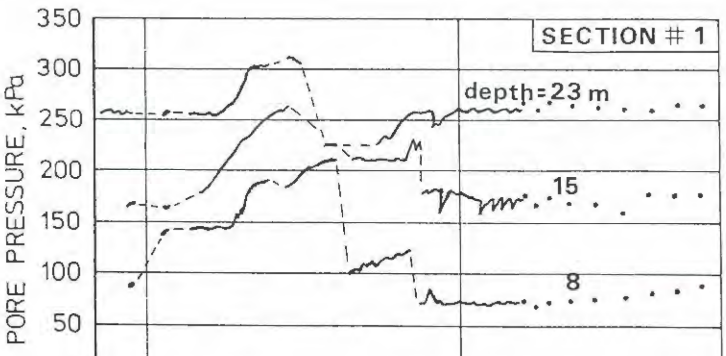


Fig. 52 Pore pressure measurements at Munkedal - toe of the slope.

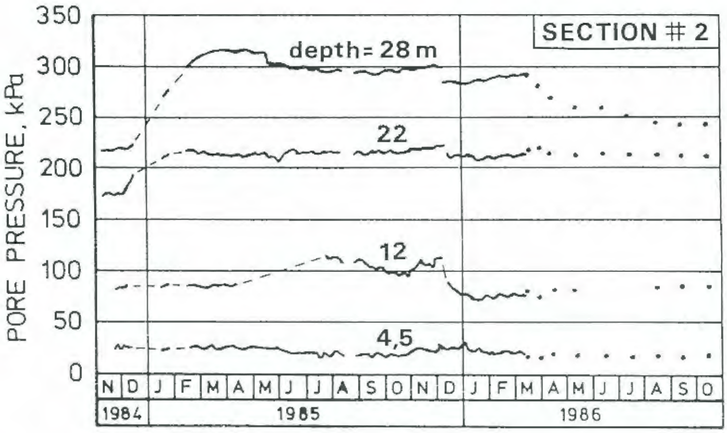


Fig. 53. Pore pressure measurements at Munkedal - crest of the slope.

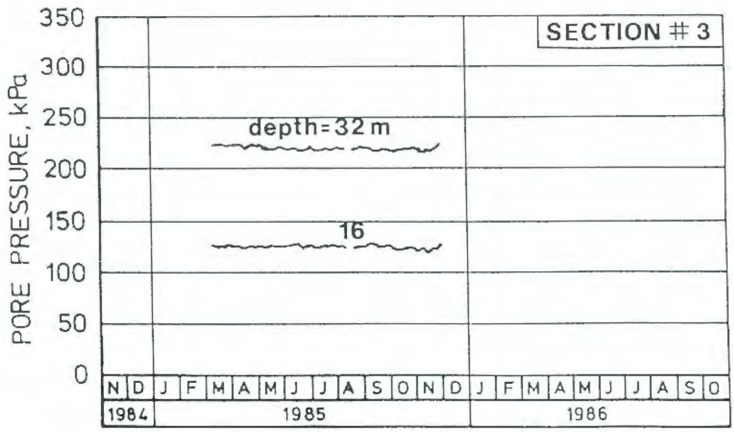


Fig. 54. Pore pressure measurements at Munkedal - behind the slope.

At the beginning of 1985, the measurements in section 1 and 2 showed an increase of the pore pressure in the most unstable zone. The pressures stabilized to a lower level after the completion of the corrective measures by the end of the same year. The measurements performed in the reference section (section 3) showed no significant variation during this period.

Interruptions of the measurements at different moments can be observed in Figures 52 and 53. The problems that happened with the measurements at the very beginning of the recording period (November 1984 to February 1985) were due to malfunctioning of the power supply. The disturbance or interruption of the recording in section 1 (toe of the slope) between March and November 1985, were mostly due to the heavy construction traffic during the excavation of the new river bed and the construction of the pressure berm which took place during this period. However, the interruption observed during the same period in the piezometer installed at 12 m in section 2, was due to another problem which will be discussed later in Section 7.6.3.

The next section presents various problems encountered during the period of measurement; the probable sources of these problems are also described, together with their possible solutions.

7.6 PARTICULAR PROBLEMS DURING THE PERIOD OF MEASUREMENT

7.6.1 Improper connection of the transducers

One of the problems that occurred at the very beginning of the period of measurement was the difficulty of obtaining a good connection between the transducers and the filter tips. Figure 55 shows the measurements made with transducers improperly connected (depth 8 m and 15 m) from November 2nd to December 6th; after this period the transducers were removed, re-calibrated and re-installed correctly.

The problem occurred once more between February 7th and March 7th, 1985 for the piezometer installed at 15 m, but it was easily detected from the measurements (see Figure 56) and the transducer was re-installed correctly.

When the connection between transducer and filter tips is not made adequately, the pressure recorded may correspond to the height of water in the pipe, but the value measured may be quite different if the needle has begun to penetrate the membrane without passing through it completely. If this situation occurs, the pressure recorded may be very high or very low without any logical explanation.

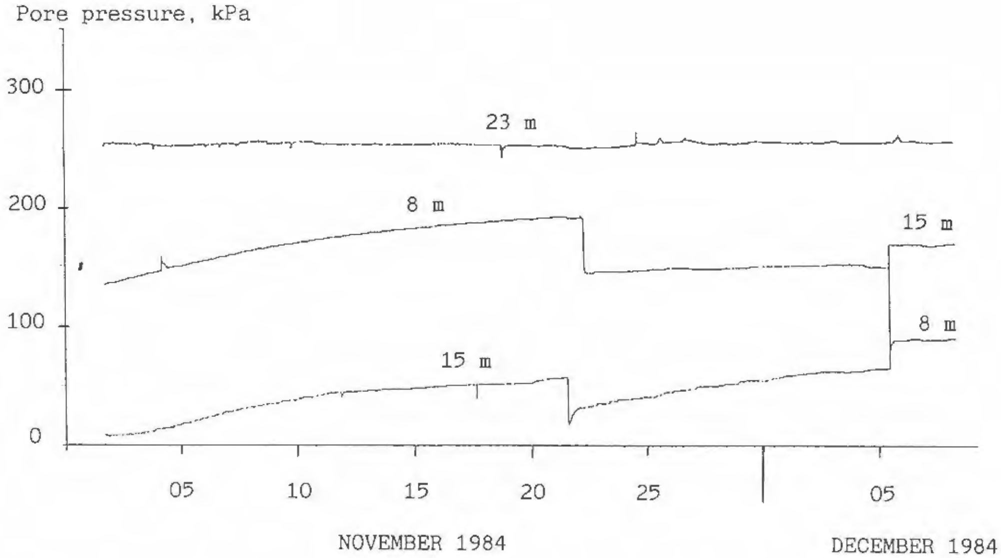


Fig. 55. Pore pressure measurements performed with improperly connected transducer, Munkedal - Nov/Dec 1984.

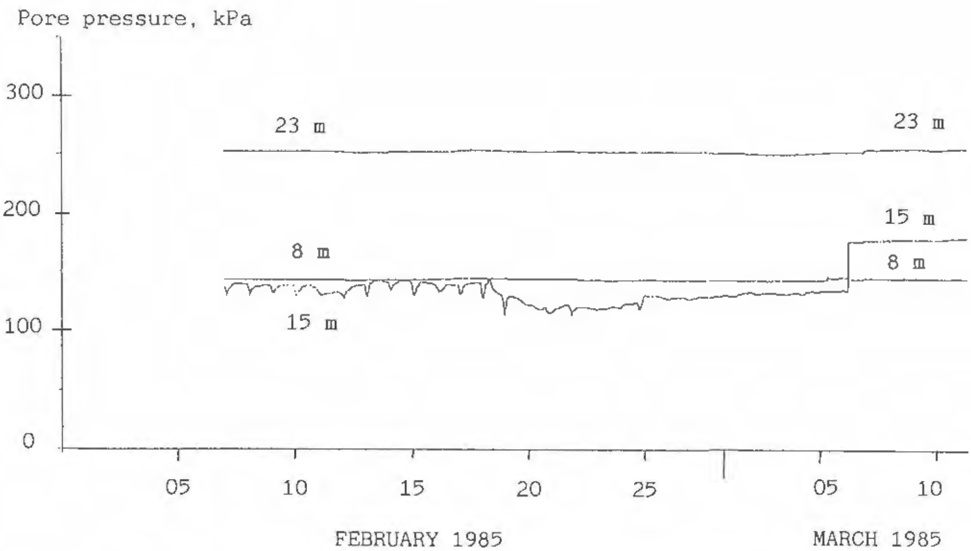


Fig. 56. Pore pressure measurements performed with improperly connected transudcer, Munkedal - Feb/Mar 1985.

There are two reasons why the needle may not penetrate the membrane. The first is that the transducer may not be heavy enough and that the rubber membrane due to its rigidity stops the needle; this problem can be solved easily by adding weight on top of the transducer. The second reason is related to a fabrication problem, since it happened a that the membrane used was thicker than usual or even that two membranes were installed in the same tip; the only solution in this case is to use a longer needle.

It is very important to be sure that the transducers are properly connected to the filter tips before they are further linked to the recording system. The transducer should always be connected to a manual reading device during installation in order to be able to follow the behaviour of the pressure when the membrane is reached and penetrated. When the pressure seems to stabilize after the disturbance created by the penetration of the membrane, the transducer may be connected to the reading system.

7.6.2 Malfunctioning of the transducers

Sometimes during the period of measurement, the variations in pore pressure showed an irregular configuration as, for example, in the measurements made at 22 m depth between February and April 1985, Figure 57. After a comparison with the measurements made at different levels at the same section, it was assumed that the variations registered were due to a malfunctioning of the transducer installed at this level. The transducer was therefore removed and a new one was installed on April 9th; the measurements subsequently remained stable, which proved that our assumptions were correct.

This type of instability may be caused by various imperfections: incorrect sealing of the membrane, deterioration of the electric cable, improper welding of the connections, etc ... . Such problems may also be due to a defect in one of the electronic elements used in the transducer.

This problem has been encountered a few times during the period of measurement, but it was always identified and solved rapidly due to the flexibility of the system, which makes it possible to change the transducers in such cases.

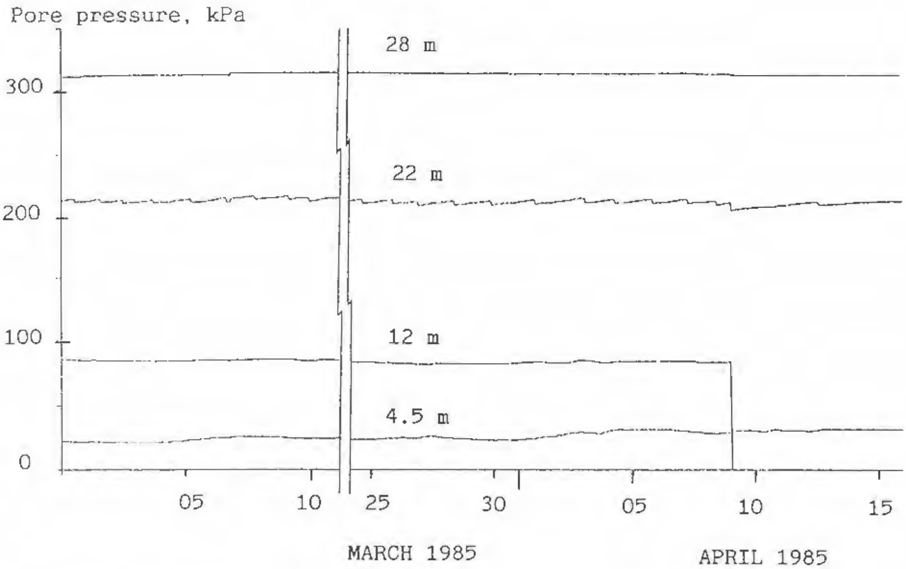


Fig. 57. Pore pressure measurements performed with defective transducer, Munkedal - Mar/Apr 1985.

7.6.3 Difficulty of re-installing the transducers

Occasionally, the transducers removed for a calibration control could not be re-installed on the filter tip. This problem occurred first in December 1984 in section 2, where a piezometer was to be installed at 17 m depth. A few days after the installation, the tranducer was pulled up for calibration. Thereafter, the transducer was lowered freely down to about 0,3 m above the filter tip, where it suddenly stopped. The transducer was subsequently pulled up with great difficulty and, despite many attempts, it was impossible to re-install it on the filter tip. Due to the very short period of measurement, the results were not presented in Figure 53.

The same problem occurred once again in the same section with the piezometer located at 12 m depth (April 1985). However, in this case it was possible to reconnect the transducer some months later (July 1985) (see Figure 53).

It is difficult to explain with certainty what happened in these two cases. The most logical explanation is that the filter tip was displaced due to movement in the surrounding soil and that the joint located about 0,3 m above the tip was bent so that the transducer stopped at this level and could not be lowered deeper. The soil around the piezometer located at 12 m has probably moved further between April and July; the lateral forces on the filter tip were then released and the joint was straightened, which would explain why the transducer could be reinstalled.

Unfortunately, very little can be done concerning this problem. It is important to be very careful during the installation of the filter tips, making sure that the joints are sufficiently tight so that no movement is possible at this level. It is also important to be sure that nothing inside the pipe could make it difficult, or even impossible, to lower the transducer in the event of uneven movement.

8. DISCUSSION - CONCLUSIONS - RECOMMENDATIONS

The measurements performed at Örebro and Linköping showed that normal variations in pore pressures can be measured satisfactorily by using any of the systems installed. The values obtained with the open systems showed very good agreement with those given by the closed systems. This means that even open systems may be used for measuring natural variations in the pore pressure in clayey soils when these variations are slow enough for the system to stabilize despite its long response time. It appears from the measurements performed on these two sites that the water movement necessary for the open systems to register natural pore pressure variations is sufficient, despite the low permeability of the soil.

The behaviour of relative pressure transducers was studied from the measurements performed at Skå-Edeby. The results of this study showed that the use of such transducers may lead to serious errors in the interpretation of the measurements if the atmospheric pressure begins to affect the transducers. The variations registered by the system may then be incorrectly classified as pore pressure variations, while they actually are fluctuations in atmospheric pressure. This problem may occur when the device used for transmission of atmospheric pressure to the transducer becomes defective, and may be very difficult to detect unless measurements of atmospheric pressure are performed simultaneously. Because of this important problem, the use of relative pressure transducers does not appear to be adequate in a warning system.

The next step in the analysis of different measuring systems was the study of the influence of atmospheric pressure on measurements performed with absolute pressure transducers. The comparison of the value obtained with relative pressure transducers and absolute pressure transducers clearly showed that the fluctuations registered by these two systems are quite different. However, the same comparison made after correction of the values obtained from absolute transducers for atmospheric pressure showed very similar variations. These comparisons, made before and after the correction for atmospheric pressure, indicate that the measurements performed with absolute pressure transducers must always be corrected for the atmospheric pressure in order to obtain the actual variations in pore pressure. This correction is especially important when absolute transducers are used in a warning system since variations in atmospheric pressure may be wrongly interpreted as pore pressure variations, which could lead to "false alarms" if any "critical value" is reached.

Even though the study performed at Linköping gave interesting and useful results regarding the influence of the variations in atmospheric pressure on the pore pressure measurements, some aspects of this influence are still unknown. One of these unknown aspects is the extent of this influence at different depths, which would be a significant factor in the choice of the "critical values" to be used in a warning system.

The measurements performed at Munkedal over a long period have revealed certain problems related to the automatic measuring system used. One of the most common problems occurred during the installation of the transducers on the filter tips, whilst a bad connection affected the measurements performed afterwards. This showed the importance of using a manual reading device connected to the transducer during this operation in order to make sure that the installation is perfromed correctly. This also showed the necessity of regular controls of the installation by competent personnel.

The measurements showed that a reliable long-term measuring and recording system must include a number of essential characteristics. The system must be flexible and make it possible to check the instruments used by controlling the calibration parameters. It must also be possible to measure manually the pore pressure at different intervals in order to check the values registered by the permanent installation. The use of the filter tips of the BAT type with removable transducers has proven to be an excellent choice. This combination makes it possible to disconnect the transducers and to take them up for calibration on the site or in the laboratory. This also provides an opportunity to check the condition of the filter tip (clogging, leakage) and to measure the pore pressure with another transducer and a manual reading device. This system has the flexibility required in a continuous reading and recording system since any defective transducer can be detected, removed and replaced rapidly. It is also very reliable if the control routine is performed regularly.

The measurements made at Munkedal were among the first series of this type made by the SGI where the pore pressure was registered automatically at very short intervals. The first results were sometimes difficult to analyse due to the different problems arising through the use of a new system. However, these problems were overcome and reliable measurements were subsequently performed. The measurements showed an increase in the pore pressure in the most dangerous zone as delimited by the slope stability analysis (see Bergdahl and Tremblay, 1987). This observation is very promising and accentuates interest in eventually using the pore pressure as a decisive parameter in a slope stability control system.

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