Calibration of Piezocones for Investigations in Soft Soils and Demands for Accuracy of the Equipments

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This report deals with the calibration of cone penetration equipments that should be performed before they are used for investigations in soft soils.

The purpose of the report is to describe the level of accuracy that can be obtained in the test results and how this is achieved, and also the working principles of the equipment and its inherent sources of error.

The report is intended for the companies and staff performing this kind of test, the manufacturers of this type of equipment and the engineers interpreting and using the results.

The investigations and the development of the procedures described in the report were performed as part of a larger investigation concerning the use of new in situ testing devices for investigations in loose to medium dense soils. Other parts of this project have been reported in:


- Laboratory calibration of cones for combined cone penetration testing and pore pressure sounding, Larsson and Eskilsson (1988). Swedish Geotechnical Institute, Varia No. 223. (In Swedish)


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1. SUMMARY AND CONCLUSIONS

Piezocone tests in soft soils bring special demands for accuracy and calibration of the equipments. Normally, cones with a load capacity of 5 tons or more are used also in soft soils. This means that often less than one per cent of the measuring range is used.

Many of these cones are accurate enough to be used also in soft soils, provided they are recalibrated for the smaller ranges. This calibration should comprise

- the usual calibration of scale factor, linearity, hysteresis and non return to zero for the actual range
- a careful calibration of area factors for all measurements which can be affected by pore water pressures
- a careful check of all possible cross-talk effects between the measured parameters and also effects of friction in the O-ring seals
- a calibration of the temperature effects on the measured parameters

At present, there is a European standard for the geometry of the piezocone and a recommendation has been submitted to the International Society for Soil Mechanics and Foundation Engineering for use of the cone penetration test as a reference test. However, this recommendation is very vague about the piezocone and also needs to be more precise in other respects in order to be of use for tests in soft soils.

The recommendation specifies that the accuracy of the equipment should be such that the error in any measurement should not be greater than

\[
5\% \text{ of the measured value or}
\]

\[
1\% \text{ of the maximum value of the measured resistance in the layer under consideration}
\]

whichever is the greater. These limits should include all sources of errors in calibration, cross-talk effects, eccentricity of loads and temperature effects.
In soft soils, it is impossible to fulfill such demands and the limits have to be replaced by, or supplemented with, practically attainable limits expressed in kPa. This will also help to avoid subjective interpretation of what "measured values" and what "layer under consideration" means. Tentatively, such limits could be that the maximum error taking all aspects into consideration should not be greater than

- 20 kPa for tip resistance
- 2 kPa for sleeve friction
- 1 kPa for pore pressure

The recommendation to ISSFME specifies that the cones shall be temperature compensated and that the error due to temperature effects shall be included in the maximum allowable error. This should also be the case in the tentatively suggested limits for tests in soft soils, although the temperature compensation needs clarification. Experience has shown that the practically attainable limits for permanent zero shifts at temperature changes in 5 ton cones are about

- 2.0 kPa/°C for tip resistance
- 0.1 kPa/°C for sleeve friction
- 0.05-0.1 kPa/°C for pore pressure (depending on the pressure range for the transducer)

and this precision should also be demanded.

The results from both field tests and calibrations have made it absolutely clear that the measured tip resistances and sleeve frictions have to be corrected for pore pressure effects. Moreover, in soft soils the measured values also should be corrected for other factors, such as cross-talk, O-ring frictions and unequal pore pressures at the ends of the friction sleeve.
The corrected values of tip resistance \( q_T \) and sleeve friction \( f_T \) then become

\[
q_T = q_M - R_c - c \cdot f_M + u(1-a)
\]

\[
f_T = f_M + f_f - u \cdot b - \Delta u \cdot A_y/A_S
\]

where

\( q_T \) = Total tip resistance

\( q_M \) = Measured uncorrected value of tip resistance

\( R_c \) = Correction of tip resistance due to 0-ring friction at unfixed friction sleeves (to be applied when a positive reading of \( f_M \) indicates that the friction is mobilized)

\( c \) = Cross-talk factor between measured friction and tip resistance

\( f_M \) = Measured uncorrected value of sleeve friction

\( u \) = Pore pressure between the tip and the friction sleeve

\( a \) = Net area factor

\( f_T \) = Total sleeve friction

\( f_f \) = Correction for sleeve friction due to 0-ring friction at unfixed friction sleeves (to be applied when a positive reading of \( f_M \) indicates that the friction is mobilized)

\( b \) = Unequal end area factor

\( \Delta u \) = Difference in pore pressure between the lower and the upper end of the friction sleeve

\( A_y \) = Upper end area of the friction sleeve

\( A_S \) = Outer surface area of the friction sleeve

The most uncertain correction is the correction for unequal pore pressures at the ends of the friction sleeve. The pore pressure at the upper end is seldom measured, but has to be estimated from empirical experience. This problem can be minimized by keeping the end areas small.
A further correction could be made for temperature effects. The temperatures, however, are not regularly measured and, even then, only the permanent zero shifts could be accounted for, not the transient errors. It is therefore of great importance that the cone has a temperature close to the ground temperature when taking zero readings and at the start of the test. A built-in temperature transducer is of great help in ensuring that this requirement is fulfilled.

When using water in the filter and the pore pressure measuring system, the dry crust has to be predrilled so that the test starts from the bottom of an open water-filled hole. Care has to be taken to ensure that the predrilling is deep enough to avoid any negative pore pressures. Alternatively, glycerine can be used as a pressure transmitting fluid. Then, preboring does not appear to be required in many dry crusts with a thickness of 1 to 2 metres. The use of silicone oil is not recommended for testing on-shore.

Many piezocone equipments use reading frequencies of one reading at every 50 mm of depth or even longer intervals. This can be considered sufficient for tip resistance and sleeve friction, but such a procedure entails that the detailed information on the stratigraphy, which can be obtained by continuous recording of the pore pressure during penetration, is largely lost. It is therefore recommended that pore pressure readings be taken (and stored) at every 10 mm of penetration or even more frequently.
2. INTRODUCTION

There is a great demand for rational and accurate methods of investigating soil profiles, concerning both their stratigraphy (and associated soil classification) and the engineering properties of the various strata.

Various equipments for measuring the resistance of the soil to static penetration of a cone have been used for a long time; first, the total penetration force was measured at the top of the penetration rods, then the tip resistance was measured mechanically by means of an inner rod system. Nowadays the tip resistance is measured electrically at the tip and the electrical signals are normally transmitted to the recording instruments at the ground surface.

The introduction of electrical measurements enabled measurement of more than one parameter and it soon became common to measure also the skin friction against the rods just above the cone on a friction sleeve.

As the use of these cones increased, a demand for standardization arose. Since 1979 there has been such a standard for Europe which is used also in most other countries, even if other types of cones are used occasionally for special purposes both in Europe and elsewhere, (the Sub-Committee on the Penetration Test 1989). The standard stipulates that the cone apex angle shall be 60° and the cross-sectional area 1000 mm² and a friction sleeve with a surface area of 15000 mm² shall be located just above the tip. The standard also stipulates certain tolerances concerning the outer dimensions of the cone and that the rate of penetration shall be 0.02 m/s.

Another type of penetration testing, the pore pressure sounding, has been used since approximately 1975, (Torstensson 1975, Wissa 1975). In this test, the pore pressure in the soil that is generated at the penetration of the cone is measured. The measurement is performed by an electrical transducer located inside the cone behind a saturated filter. The analog signals from the transducers were originally plotted against penetration depth on strip-chart recorders and it was found that, with careful saturation of the filters and the internal voids in the cone, a very detailed picture could be obtained of the stratification of fine grained and layered soils. It was also found that the measured pore pressures varied strongly with the location of the filter on the cone.
The two types of test, cone penetration and pore pressure sounding were initially used together in parallel tests, but are nowadays usually performed with piezocones which measure all three parameters: tip resistance, sleeve friction and pore pressure. The most common location of the filter is just behind the tip, but other locations, e.g. on the conical part of the tip, are also common. More advanced cones can measure the pore pressure at two or three locations along the cone and also measurements of other parameters as temperature, inclination of the cone and seismic measurements are often included.

The introduction of pore pressure measurements and the extended use of the cones in deep waters and in clays involved a number of problems as the water pressures affect not only the pore pressure readings but also the measurements of the other two parameters. This problem is accentuated at high water pressures during the cone penetration, natural or generated, and when the tip resistance and the sleeve friction are relatively low.

The problems were first observed at testing in deep waters (de Ruiter 1982) and later Lunne et al (1986) showed that, when testing in clays, totally different results were obtained with different cones unless they were calibrated and corrected for the various water pressure effects. (see FIG. 1.)

The need for the tip resistance to be corrected for the pore pressure has become generally accepted and usually a net area factor is given for the specific cone. The net area factor, $a$, is defined as $A_N / A_T$. (see FIG. 1.)

In order to avoid the influence of the pore pressure on the measured friction, most friction sleeves are designed with equal end areas and the pore pressures at both ends are assumed to be approximately equal. In clays, this assumption is a coarse simplification which may involve significant errors.

The various areas and area factors may be estimated from measured geometrical dimensions, but there is always some uncertainty about the stress transmission at the various O-ring seals. It is therefore better to calibrate them in a calibration chamber.
Total area \( A_T = 1000 \text{ mm}^2 \)

Nettoarea \( A_N \)

\[
F_T = F_c + u(A_T - A_N)
\]

\[
q_T = F_T / A_T
\]

\[
F_F = F_S + u \cdot A_L - u_U \cdot A_U
\]

\[
f_S = F_F / A_F
\]

\[
FR = f_S / q_T
\]

\[
B_u = (u - u_0) / (q_T - \sigma_{vo})
\]

Fig. 1. Example of the design of a piezocone and the influence of the pore pressure on the measured values of tip resistance and sleeve friction.
Most cones are designed to work in both soft and stiff soils from clay and organic soils to coarse sand. The maximum tip load for such cones is normally 5 or 10 tons. Good steel qualities and matching strain gages together with modern electronics usually give very good properties in terms of stability, linearity and repeatability. When using such cones in soft clays, however, only about 1% of the measuring range is used. As the measuring errors are expressed in relation to the full measuring range, this means that the low error values obtained at calibration for the full range are increased by about 100 times when only 1% of the measuring range is considered. Some cones actually have a very good accuracy even in this range, but they have to be specially calibrated for the lower stress range. Furthermore, not only the cones have to be calibrated but the whole measuring system. Even if the cones can be calibrated and are sufficiently accurate, the stability and the resolution of the recording system may be inadequate for measurements in soft soils.

In the calibrations, not only the effect of pore pressure on the other parameters but also all other interferences between the different parameters have to be investigated. Because of the complex design and sealing of the cones, there is a high risk of cross-talk effects either inherent or introduced at assembly and tightening of the various parts. Also these effects are magnified in the low stress ranges.

The cones also have to be calibrated for temperature effects. The effects of a change in temperature on the output from electrical transducers are often small if proper materials and installation techniques have been used. The same is valid for the output from strain gages when they are carefully temperature compensated. The errors, however, become magnified if only a small part of the measuring range is used. In all cases, the temperature effects should be calibrated to ensure proper installation of transducers and temperature compensations.

Another problem is that even if the cone has good stability for permanent temperature changes, it cannot usually be compensated for the changes that occur while there is a temperature gradient in it. If a cone is lowered into a water bath with a different temperature, it takes some minutes before the entire cone has reached the new temperature. During this time, there will be temperature gradients in the cone and varying outputs from the transducers, even if they return to the original values after the temperature has stabilized. The same happens at the start of a penetration test in the field, where it is seldom possible to adjust the cone temperature exactly to the ground temperature at greater depth before the penetration starts. During the first metres of a cone penetration test, there is therefore usually a temperature gradient in the cone and calibration has to be performed to assess the possible error.
When using the variations in generated pore pressures to estimate the stratigraphy and the existence of any varves and thinner layers, it is essential for the measuring system to respond very fast to changes in water pressure. The response-time is normally mainly dependent on the degree of saturation in the filter and the cavities at the pore pressure transducer, but may also depend on the design of the cone and the transducer and also on the electrical components used in the measuring system. It is normally not possible in the laboratory, to simulate the conditions in the soil in situ during penetration but a simple check of the response of the complete measuring system with a saturated cone and filter for a stress change in surrounding water ought always to be made.

Also other measured parameters such as temperature and inclination should be calibrated to ensure what is actually measured and with what accuracy.

A seismic output does normally not have to be calibrated, but this can be done with special equipment if there is any doubt about the correct of the output function or if the information provided by the manufacturer is insufficient for the user's purposes.

Calibration may be divided into three categories:

A. Calibration that has to be performed in order to enable an interpretation of the measured data. This includes:

Calibration of the three basic measurements: tip resistance, sleeve friction and pore pressure in the appropriate stress ranges.

Calibration of all area factors and other cross-talk effects between the measurements.

Calibration of temperature effects.

B. Calibration that ought to be performed. This includes:

Calibration of pore pressure response-time.

Calibration of optional parameters e.g. temperature and inclination.

C. Calibrations that may be performed if the need arises, such as:

Calibration of seismic measurements.
3. BASIC CALIBRATION

3.1 Calibration equipment

The necessary calibration equipment consists of a loading device where an axial load can be symmetrically applied to the cone without introducing any bending forces. Usually some kind of hydraulic or pneumatic press is used, but for very low stress ranges also weights can be applied. When a press is used, there also has to be a very exact system for measuring the applied force. In most cases, high-precision load cells are used. To enable satisfactory calibration over a wide range of stresses, a set of load cells with different ranges should be used. Special adapters have to be used to transmit the forces to the cone tip and to the friction sleeve respectively, and also to transmit the force to the upper end of the cone. The adapter at the top is designed to accommodate a signal pick-up or to carry the signal cable. The adapters should also be designed with ball seats in the outer ends to ensure alignment of force transmission.

![Fig. 2. Calibration press with cone and reference stress measurement system.](image-url)
For calibration of the pore pressure transducer, a hydraulic or pneumatic pressure system is required. The simplest system consists of compressed air and an air pressure regulator. The regulated air pressure is led both to the pore pressure transducer and to a high precision system for measurement of the applied reference pressure. In simple calibrations the flexible pressure line can be connected directly to the pore pressure transducer by a threaded connector replacing the cone tip. In more advanced calibrations, the lower part of the cone (including the friction sleeve) is inserted into a calibration chamber. The response of all measured parameters to a change in external air or water pressures can then be studied by increasing the pressure in this chamber.

Fig. 3. Calibration chamber for piezocones.
The calibration chamber is always placed inside the calibration press. This is a safety measure against the risk that the cone could be pushed out of the chamber by the internal pressure and also enables application of both axial forces and surrounding water pressures simultaneously on the cone.

3.2 Calibration of tip resistance

At calibration of the tip resistance, an adapter with a conical cavity with an angle of 60° providing a well-fitted seating for the cone tip is used. At the upper part of the cone, the adapter matching the specific cone design is attached. A high precision load cell adapted for the stress range for which the tip resistance is to be calibrated is mounted in the press. The cone is placed in the press with steel balls at the outer ends of both adapters and great care is taken to ensure verticality. The cone and the load cell are connected to their respective electronic measuring systems and both are switched on and warmed-up for sufficient times. The data acquisition system for the cone is either supplied with a special calibration programme or facilities for taking single readings or, alternatively, the normal testing programme is run and readings are triggered by manual rotation of the depth recording wheel.

After reading off a baseline for the unloaded cone, the load is increased in steps up to the maximum force and then unloaded in steps to zero load. This is repeated in a number of cycles to enable evaluation of the characteristics; scale factor, linearity, repeatability, hysteresis and zero shift. Readings of all other parameters should be taken simultaneously with the readings of the tip resistance for control of eventual cross-talk effects (interference between the measured parameters).

In the calibration, the cone should always be connected to the data acquisition system that will be used in the field tests, as it is the accuracy and resolution of the whole measuring system that are of practical importance. Sometimes, it is valuable to have an extra measuring system connected in parallel to measure the actual signals coming out of the cone. Thereby, it is possible to localize possible problems with stability and resolution, i.e. whether these are in the cone itself or in the data acquisition system. In the latter case the problem may be either in the electronic parts or in the interpretation programme.
Fig. 4. Example of a calibration curve for tip resistance in a very low stress range and explanation of the calibrated characteristics.
FIG. 4 shows a calibration curve for tip resistance in a 5 ton cone in the range 0-200 kPa. In this range the maximum error, taking all factors into account, is about 6 kPa. If, instead, the calibration factor for the full range up to 50 MPa is used, this error will double to 12 kPa. It should be observed that this is not the accuracy of the measurements that can be obtained in the field because other error sources, such as cross-talk and temperature effects, are added to the values obtained in this type of calibration.

3.3 Calibration of sleeve friction

At calibration of the sleeve friction, the tip of the cone is unscrewed, the filter and mud seals, if any, are removed and the cone with the friction sleeve is inserted into another adapter. This adapter has a cylindrical cavity fitting the friction sleeve. At some depth in this cavity, the inner radius is reduced by the same amount as the thickness of the lower end of the friction sleeve. Below this level, the cavity is so deep that all other parts of the cone are free when the cone is fully inserted into the adapter. The friction sleeve then rests on the plane ledge inside the adapter and all axial forces are transmitted by the friction sleeve. Some minor forces may actually be transmitted to the measuring elements for tip resistance by friction in O-ring seals. These forces are normally overcome by the weight of the cone itself and thus do not play any part in the calibration. If the cone for some reason should be turned upside-down in the press, the O-ring forces may show up in the very low stress ranges. When evaluating the measured friction and the accuracy in the measurements for cones with unfixed friction sleeves, (i.e. sleeves that are not rigidly fixed to the measuring body e.g. by being screwed on), also these friction forces should be considered, however. For such cones, the real friction on the outside of the sleeve has to overcome both the weight of the friction sleeve itself and the friction in the O-ring seals before the changes in sleeve friction are properly registered by the measuring element. This combined force error is often in the order of 20 N, which corresponds to an error in measured friction of about 1.3 kPa.

If need be, the reference load cell is replaced by one better suited to the maximum force that is to be applied. The cone is then placed in the press in the same way as at calibration of the tip resistance and the same procedure is followed.

FIG. 5 shows a calibration curve for sleeve friction in a low stress range. The combined maximum error in this calibration is only about 0.75 kPa. In actual field testing, however, it should be observed that in addition to this value there is the error due to friction in the O-rings and the uncertainty in correction for unequal end pressures.
3.4 Interference between tip resistance and sleeve friction

The readings of tip resistance and sleeve friction should ideally be totally independent of each other. This, however, is not always the case. Many cones are designed as so-called "subtraction cones" where one measuring element measures the tip resistance and another element measures the sum of the tip resistance and the sleeve friction. The sleeve friction is then calculated from the difference in the outputs from the two elements. This procedure, in all aspects, puts very high demands on the stability and the measuring accuracy of these elements and their matching together.
The elements measuring the tip resistance and the sleeve friction are almost always placed on different parts of the same steel body and it is not absolutely certain that the stress distribution in this body is such that the different parts are totally unaffected by stress changes in the other part. By studying the responses in both the elements measuring tip resistance and sleeve friction at the separate loadings of the tip and the sleeve, the eventual interference (cross-talk) between the measurements can be observed. This interference should be small, but if it exists then its relative importance often increases at lower stress ranges. Usually, it is the measured tip resistance that is significantly affected by applied friction.

FIG. 6 shows the interference between applied friction and corresponding response in the measuring element for tip resistance in four different cones. Two of the cones are 5 ton cones of the subtraction type and the other two are compression type cones, one 5 ton cone and one 0.5 ton cone. The results show larger interferences for the subtraction cones. Especially for one of them, this interference alone would make it impossible to achieve the desired accuracy in measured tip resistance in soft soils, unless it is taken into account and corrected for.

![Graph showing interferences between applied friction and measured tip resistance for four different cones.]

Fig. 6. Interference between applied sleeve friction and measured tip resistance for two subtraction cones and two compression cones.
A special kind of interference between tip resistance and applied sleeve friction has been observed at testing and calibration with hard filters. If the dimensions of the filters exceed the allowable tolerances, then large stresses may be introduced when the cone is assembled and tightened. These built-in stresses may greatly affect the distribution of the stresses measured on the friction sleeve and on the tip. This type of error must be avoided and it is recommended to check all filters in such a way that after the cone has been assembled and tightened it should be easy to rotate the filter with the finger tips.

Another special kind of interference between friction and tip resistance may occur if the friction sleeve is not fixed. A certain minute movement of the friction sleeve in relation to the main body of the cone is then required before any friction is registered. During this movement a friction is mobilized in the O-ring seals and this force may partly be transferred to the element measuring tip resistance. The maximum frictional force is typically in the order of 15 N. Assuming an even distribution between the frictional forces in the seals at both ends of the friction sleeve, this interference would be in the order of 8 kPa on the tip resistance. This type of interference and its approximate order of size have been verified in calibrations of the friction sleeve with the cone turned upside-down to avoid prestressing by the weight of the cone itself. The interference also shows up at careful calibration of the area factors.

Most cones use commercial high quality pressure transducers to measure the pore pressure. When these transducers are properly mounted there should be no interference from the other stresses in the cone on the pore pressure measurements. If they are not properly mounted, or if the cone manufacturer has used an inferior transducer or a home-made pressure sensing element forming part of the main steel body, then the interference may be considerable and even unacceptable.

3.5 Calibration of pore pressure

At calibration of the pore pressure, the cone is either inserted into the calibration chamber or the tip is unscrewed and replaced by a pressure adapter. The flexible pressure line is connected to the chamber or alternatively to the adapter. When the chamber is used, the lower part of the cone should normally be hanging free inside the cell with no load on the tip or the friction sleeve. The cone is connected to the data acquisition system and all electronics, including the reference pressure measuring system, are allowed to warm up.
At cone penetration tests in clays, very high pore pressures are developed. This requires calibration for high stress ranges. At the same time, it is often important to determine accurately the much lower in situ water pressures in more permeable layers at various depths, where the penetration may be stopped to allow for dissipation of excess pore pressures. The pore pressure measurements may therefore have to be calibrated for both high and low stress ranges and the reference system should preferably contain very accurate units for both ranges.

Calibration is performed with step-wise loading and unloading in the same way as for the other parameters.

FIG. 7. shows a calibration of a pore pressure transducer. The actual transducer is a high-quality commercial transducer and the maximum error for the whole range is about 0.1 kPa. In addition to this error, there are the temperature effects and possible cross-talk effects.

![Fig. 7. Calibration of pore pressure.](image)
3.6 Interference between pore pressure and tip resistance

Due to the design of the cones, the measured tip resistances are affected by the pore pressure in the soil as this water pressure acts not only on the outer surfaces of the cone but also inside all open cavities in the cone. At the joint between the tip and the friction sleeve, the pore pressure acts in the opening between these two parts and the effect of the pore pressure on the tip resistance depends on the geometrical design of the cone, FIG. 8.

\[ F = u \cdot A_L \]

Fig. 8. Effect of pore pressure in the opening between the tip and the friction sleeve;

The pore pressure in the opening creates an uplift force on the friction sleeve and an equal downward force on the tip \(^*\). The magnitude of this force depends on the area of the lower end of the friction sleeve.

\(^*\) In practice, there may be a minor difference in these two forces as the diameter of the tip may be slightly smaller than the outside diameter of the friction sleeve according to the allowable tolerances.
This interference of the pore pressure on the measured tip resistance occurs in all cone designs and increases with increasing lower end areas of the friction sleeve. In cones where the pore pressure is measured and the filter is placed in the slot between the tip and the friction sleeve, the tip resistance can easily be corrected for this pore pressure interference by adding the force \( u \cdot A_L \) to the measured force on the tip. This correction cannot be made for cones without pore pressure measurements. For cones where the pore pressure has been measured only at some other filter location, an assumption has to be made about the pore pressure distribution along the cone.

The effect of the pore pressure on the measured tip resistance can easily be demonstrated in the calibration chamber, FIG. 9.

![Image of cone designs](image)

**Case A**
- Corrected by \( u \cdot A_L \)
- \( A_L = 200 \text{ mm}^2 \)

**Case B**
- Sealed openings

**Fig. 9. Examples of interference between pore pressure and tip resistance in different cone designs with and without pore pressure acting in the opening between the tip and the friction sleeve.**

The results from the calibration chamber clearly show that the influence of the pore pressure inside the cavities on the measured tip resistance is large, that it increases with increasing lower end area of the friction sleeve and that it can be corrected by adding the product of the pore pressure and the lower end area of the friction sleeve to the measured force on the tip. The influence is further illustrated if the openings are sealed off by a rubber membrane so
that the pore pressure is prevented from acting inside the cavities in the cone. The measured tip resistances then become equal to the applied pressure, irrespective of cone design.

3.7 Interference between pore pressure and sleeve friction

In the same way as the pore pressure affects the forces on the tip, it also affects the forces on the friction sleeve. In the friction sleeve, however, there are two end areas that are subjected to the pore pressures. The pore pressure at the lower end acts as an uplift force and the pore pressure at the upper end as a downward force. In a case where both the two pressures and the two end areas are equal, these forces balance each other and there is no effect of the pore pressure on the measured sleeve friction. These criteria, however, cannot be completely fulfilled at penetration testing.

Most cones today have friction sleeves with equal end areas \(A_U = A_L\) in order to minimize the influence of the pore pressure. In these cones, the influence of the pore pressure on the friction force measured on the friction sleeve becomes \(\Delta F = (u_U - u_L) \cdot A_L\).

Fig. 10. Pore pressure effects on a friction sleeve.

For various reasons of design, there are still a number of cones with unequal end areas. In this case, the influence of the pore pressure becomes \(\Delta F = u_L \cdot A_L - u_U \cdot A_U\). This influence is normally much larger than the influence at equal end areas. For both cases, the friction force can be corrected in the case where the pore pressure has been measured at both ends of the sleeve. Such cones exist, but in most cones the pore pressure is measured only at one location. In the latter case, some estimation of the pore pressure distribution along the cone has to be made. This, however, is rather complicated as the distribution is a complex function of soil type, overconsolidation ratio, sensitivity and permeability among other things.
In many soils, the influence of the pore pressure effects is small on a friction sleeve with small and equal end areas, but in clays where the pore pressures range from -100 to several hundreds (or even thousands) of kPa and the real friction against the sleeve may only amount to a few kPa, the influence cannot be neglected even in this design.

The influence of the pore pressure on the measured friction can easily be shown in the calibration chamber, FIG. 11.

**Fig. 11. Effects of pore pressures on the measured friction at equal and unequal end areas and end pressures.**

The tests shown in FIG. 11. have been performed on two types of cones; one with equal end areas and one with unequal end areas. The tests have been performed with both equal end pressures and unequal end pressures. The latter mode was achieved by sealing the upper opening with a rubber membrane so that no excess pressure acted on the upper end area of the friction sleeve. As can be seen in the figure, a certain pressure is required before the influence starts to show. This is the pressure required to overcome the weight of the friction sleeve itself and the friction in the O-ring seals, (compare Section 3.3). After these forces have been overcome, the response in the friction measuring elements corresponds directly to the corrections that should be applied because of unequal areas and unequal end pressures. If an external frictional force, which is higher than is required to overcome the weight of the friction sleeve and the O-ring friction, is applied, then the response in the measured friction for pore pressure changes starts directly from zero pressure.
3.8 Interference between pore pressure and tip resistance due to unequal pore pressures on the friction sleeve

When unfixed friction sleeves are used, the effect of unequal pore pressures and end areas on the friction sleeve may affect also the measured tip resistance. Apart from the influence on the tip resistance because of mobilization of the O-ring friction when the friction sleeve moves upwards (see Section 3.4), this effect may be reversed if the combination of unequal end areas, unequal end pressures, the weight of the sleeve itself and actual frictional forces results in a downward force and movement of the sleeve. If, in some extreme design or stress situation, these forces become large, they would have to be taken up by the cone tip and result in a lower measured tip resistance which, if possible, should be corrected accordingly.

3.9 Calibration of end area factors

The relation between the different areas that are affected by the pore pressures are often given as area factors. The net area factor, \( a \), is the ratio between the total cross sectional area of the tip, \( A_T \) (normally 1000 mm\(^2\)), and the net area unaffected by counteracting pore pressures inside the cavities in the cone, \( A_N \).

\[
A_N \approx A_T - A_L
\]

\[
a = \frac{A_N}{A_T} \approx \frac{(A_T - A_L)}{A_T}
\]

Corresponding area factors could be given for the influence on the measured friction using the area of the friction sleeve as a reference. Lunne et al (1986) suggested an unequal end area factor, \( b \), where

\[
b = \frac{A_L - A_U}{A_S}
\]

where \( A_S \) = surface area of the friction sleeve (normally 15 000 mm\(^2\))

This factor is often used, but other definitions occur in the literature. It is therefore prudent to specify which definition is used and to also give the end areas in real numbers in order to avoid confusion.
The areas and the area factors can be calculated from the measured dimensions of the cone. When there is any doubt about how the pressures are acting, e.g. at the O-ring seals, the areas can be calibrated in the calibration chamber. The area factor and the lower end area of the friction sleeve are then calculated from tests of the response in measured tip resistance to changes in chamber pressure without any external sealing of the openings in the cone. The net area factor is calculated as

\[
a = \frac{\Delta \text{measured tip resistance}}{\Delta \text{applied chamber pressure}}
\]

and the lower end area of the friction sleeve \(A_L\) is calculated as

\[
A_L = (1 - a) \cdot A_T
\]

In this type of calibration it should be observed that, when unfixed sleeves with unequal end areas are used, an extra force may be applied to the measuring element for the tip resistance when the friction sleeve tends to move and the friction in the O-ring seals is mobilized. This results in a non-linear relation between the applied chamber pressure and the measured tip resistance. In this case, the area factor is evaluated from the straight line relation at higher pressures and the frictional error, \(R_c\), is evaluated at the intersection between this line and the axis for measured tip resistance, FIG. 12.

*Fig. 12. Evaluation of net area factor \(a\) and friction error \(R_c\).*
If the end areas of the sleeve are equal, there should be no response in the friction measuring element in this type of test. If the end areas are unequal and the lower end area is larger than the upper (or if the sleeve is fixed), then the difference in area can be calculated from the linear response in the friction measuring element for the changing chamber pressures after the corresponding initial friction has been overcome

\[
\Delta A = \frac{\Delta \text{measured friction (kPa)} \cdot A_S}{\Delta \text{applied chamber pressure (kPa)}}
\]

The upper end area \( A_U \) is then calculated as \((A_L - \Delta A)\).

If the upper end area of an unfixed sleeve is larger than the lower, then the procedure would have to be changed. In order to evaluate the net area factor and \( A_L \), the calibration would have to be performed with the opening above the friction sleeve sealed off from the chamber pressure so that no pressure changes occur at this end. The net area could then be evaluated as before and the lower end area could be evaluated from both the response in the tip resistance and the response in the sleeve friction. The seal is then removed and the calibration is repeated. The differential area and the upper end area are calculated from the difference in responses in tip resistances and sleeve frictions between the two cases.

For both types of relations between the two end areas, the upper end area for unfixed sleeves can be checked by sealing the lower opening and studying the change in response in tip resistance compared to the unssealed response. In this test, the pressure is allowed to act fully on the upper sleeve area and the readings from the pore pressure transducer inside the cone can be used to check that there is no pressure change at the lower end area.

Comparisons between the areas and area factors estimated from geometrical measurements and corresponding values obtained in calibrations for two types of cones are shown in TABLE 1.

As shown in the table, very similar values are normally obtained in the calibrations as compared to those estimated from geometrical measurements. The calibration helps to verify the measurements and the working principles. It also clarifies questions and helps to identify and quantify frictional errors. Furthermore, it helps to avoid conceptual mistakes in the geometrical estimations, which are fairly easy to make.
Table 1. Measured and calibrated end areas and area factors.
("Calibration" means normal calibration with equal end pressures on the friction sleeve and "special calibration" means that one end of the friction sleeve has been sealed and the calibration has been made with unequal end pressures.)

<table>
<thead>
<tr>
<th>Cone</th>
<th>Estimation</th>
<th>Net area factor a</th>
<th>Net area factor b</th>
<th>$A^*_n$ mm²</th>
<th>$\Delta A$ mm²</th>
<th>$A_U$ mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Measured geometry</td>
<td>0.56</td>
<td>0.015</td>
<td>448</td>
<td>226</td>
<td>222</td>
</tr>
<tr>
<td></td>
<td>Calibration</td>
<td>0.56</td>
<td>0.014</td>
<td>209</td>
<td>(230)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Special calibration</td>
<td></td>
<td></td>
<td>439</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Measured geometry</td>
<td>0.80</td>
<td>0.0001</td>
<td>195</td>
<td>2</td>
<td>197</td>
</tr>
<tr>
<td></td>
<td>Calibration</td>
<td>0.80</td>
<td>0.0004</td>
<td>6</td>
<td>(178)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Special calibration</td>
<td></td>
<td></td>
<td>184</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) Measured and calibrated lower end areas may differ slightly depending on how they are evaluated. In this text it is assumed that the outer diameter of the friction sleeve is equal to the diameter of the tip. According to the specified tolerances, it may be up to 0.35 mm larger, which would increase the area by 20 mm². This difference, which varies with wear of the cone (and possibly other forces than pore pressure acting on these slightly larger areas), is neglected in this text.
3.10 Examples of measurement errors due to inadequate calibration and correction

Some of the errors mentioned above may at first appear to be petty details but before they can be neglected, they have to be quantified both in magnitude and relative importance. In penetration testing of coarse materials, many of them can indeed be considered insignificant. In soft fine-grained soils, however, the pore pressures at the tip are often almost equal to the total tip resistance. As shown by Lunne et al (1986), this results in totally different measured tip resistances which have to be corrected for the pore pressure effects.

The sleeve friction in clays has been observed to be in the same order as the remoulded undrained shear strength, (Robertson and Caspamella 1982). In Swedish clays with normal sensitivities of 10-20 and undrained shear strengths in the order of 10 - 20 kPa, this means frictions in the order of 1 kPa. Unequal end areas therefore obviously have to be accounted for. As also shown by Lunne et al (1986), this correction is not enough to bring together the sleeve frictions measured in different cone designs and further factors have to be considered.

In order to correct for unequal end pressures on the sleeve, the pore pressures at both ends should be known. This is normally not the case, and some estimation of the pore pressure distribution along the cone would therefore have to be made. The same type of estimation also has to be made in order to correct the measured tip resistance if the filter is located in another position than between the friction sleeve and the tip. As previously mentioned, this is difficult to do without comparative tests with different filter locations on the specific site as the pore pressure distribution along the cone is a complex function of soil type, stress history, sensitivity and permeability, among other things.

Test series with different locations of filters, lengths of the tips and locations of the friction sleeves have been performed at some of the test sites used by the Swedish Geotechnical Institute. This has enabled an estimation of the pore pressure at the upper end of the friction sleeve and also a comparative evaluation of the sleeve friction. This reference friction is evaluated from the difference in tip resistance obtained by a normal tip and by a tip with an elongated shoulder length equal to the shoulder of the normal tip + the friction sleeve. The tests have been performed with temperature compensated cones in holes that were predrilled, encased and water-filled through the dry crust. The cones have also been allowed to stabilize for the temperature in the predrilled holes, and the temperature effects are therefore believed to be very small. Zero-readings have been taken.
both after the stabilizations and directly after retraction of the cones following the penetrations.

The results of the tests have been corrected according to

\[
q_T = q_M - R_c - c \cdot f_M + u(1-a)
\]

\[
f_T = f_M + R_f - u \cdot b - \Delta u \cdot A_U / A_S
\]

where

- \( q_T \) = Total tip resistance
- \( q_M \) = Measured uncorrected value of tip resistance
- \( R_c \) = Correction of tip resistance due to O-ring friction at unfixed friction sleeves (to be applied when a positive reading of \( f_M \) indicates that the friction is mobilized)
- \( c \) = Cross-talk factor between measured friction and tip resistance
- \( f_M \) = Measured uncorrected value of sleeve friction
- \( u \) = Pore pressure between the tip and the friction sleeve
- \( a \) = Net area factor
- \( f_T \) = Total sleeve friction
- \( R_T \) = Correction for sleeve friction due to O-ring friction at unfixed friction sleeves (to be applied when a positive reading of \( f_M \) indicates that the friction is mobilized)
- \( b \) = Unequal end area factor
- \( \Delta u \) = Difference in pore pressure between the lower and upper ends of the friction sleeve
- \( A_U \) = Upper end area of the friction sleeve
- \( A_S \) = Outer surface area of the friction sleeve

The correction factors have been calibrated as described above.

The results of the corrections are shown in FIGS. 13 and 14.
Fig. 13. a) Measured pore pressure at the conical face of the tip and uncorrected tip resistance in clay profiles
b) Measured and corrected tip resistances obtained by cones of different designs
Fig. 14. a) Measured and corrected sleeve frictions obtained by cones of different designs
b) Corrected sleeve frictions in relation to values obtained by correlating tip resistances from cones with different shoulder lengths and also in relation to the remoulded shear strength.
In FIG. 13a it can be observed that, unless the tip resistance is corrected, the measured tip resistance is often lower than the pore pressure acting on the conical part of the tip. As the tip resistance shall be the total pressure acting on the tip, (pore pressure + effective stress), this is obviously erroneous and the tip resistances have to be corrected.

This is further illustrated in Fig. 13b where the results from two cones with different designs are shown. The uncorrected results differ and are too low for both designs. At correction, they increase to a more reasonable level and become directly compatible.

In FIG. 14a the corrected and uncorrected sleeve frictions obtained by two cones of different design are shown. One of the cones had equal end areas and for this cone the major correction is made for O-ring friction. In one of the profiles the friction readings from this cone were zero for large parts of the profile. The other cone had unequal end areas and the major correction for this cone is the correction for pore pressure. These two types of correction act in opposite directions. As is illustrated in the figure, the uncorrected curves are very different, but they merge and become compatible at correction.

In FIG. 14b the corrected sleeve frictions are compared to the sleeve friction evaluated from the difference in tip resistance in parallel soundings with cones with different lengths of the tip shoulder.

The comparison is strongly affected by the soil variability as it is very small numbers that are being compared and also because the sleeve friction is the parameter that is least repeatable between different soundings. Nevertheless, the comparisons show that the corrected sleeve frictions are in the right order of size.

The evaluated sleeve friction is also compared to the remoulded shear strength in the clay profiles. In the three profiles shown, the sleeve friction is in general found to be 1 - 5 times the remoulded shear strength. The sensitivities in the profiles range between 10 and 20.
4. CALIBRATION OF PORE PRESSURE RESPONSE

4.1 Equipment

The response of the measuring system for the pore pressure should be very fast to enable recording of sudden variations in pore pressures during penetration testing. The filters on a piezocone normally have a height of 2.5-5 mm and the standard rate of penetration is 20 mm/s. This means that the entire filter passes a certain point within fractions of a second.

There is no fixed criteria for a maximum response-time, (the time required for a change in external pore pressure to be fully recorded by the measuring system), but it should obviously be very low and in the order of milliseconds.

It is normally not feasible to simulate the in situ conditions in the laboratory with the cone embedded in various soils, but a simple check of how the measuring system responds to a sudden change in a surrounding water pressure can be made relatively easily. This requires a calibration chamber into which the lower part of the cone can be inserted. The chamber is then water-filled and sealed except for pressure lines which can be opened and closed by valves. Sudden pressure changes can be created by opening a valve to a regulated excess air pressure and then venting it by opening another valve to atmospheric pressure. This procedure gives a trapezoidal pressure wave with a fairly long amplitude. Shorter sinus-shaped pressure impulses can be obtained e.g. by connecting another pressure cell where the pressure is regulated by a loaded piston. Such cells are often used for the purpose of maintaining a constant pressure. The short pressure impulse is then obtained by hitting the top of the piston with a hammer. Typical stress-impulses of say 100 kPa with a duration from zero to peak and back to zero in about a tenth of a second can easily be created in this way. The short stress-impulses make it possible to evaluate both time-lag and degree of response.

In order to evaluate the response in the cone, a reference transducer has to be installed inside the chamber. This transducer is connected to a signal conditioner and the output signal is led to a dual-channel memory oscilloscope in such way that no time delays are introduced for the signal. The output signal from the cone is led to the other channel on the oscilloscope. This may require extra provisions depending on the design of the cone and its data acquisition system.
The use of a dual-channel memory oscilloscope (or some other extremely fast-reading data acquisition system) is necessitated by the very rapid processes that are to be measured. Such investigations have previously been performed at the Swedish Geotechnical Institute, (Larsson and Eskilsson 1988). An arrangement for calibration of the pore pressure response in a cone is shown in FIG. 15.

Fig. 15. Arrangement for testing response-times in piezocones.

4.2 Calibration of response

The usual check on a cone consists of careful saturation of the cone and the filter with de-aerated water or any other preferred pressure transmitting fluid. The lower part of the saturated and assembled cone is inserted into the calibration chamber which is filled with water. The electronics are connected and warmed-up and the water in the chamber is subjected to pressure impulses. At these impulses, the oscilloscope is triggered and the time-pressure curves from both the reference transducer and the cone are shown on the screen.
For this type of test, the response in the cone should be total and immediate, (delay less than about 1 millisecond). For most cones using commercial high quality pressure transducers these demands are met and curves such as those shown in Fig. 16 are obtained.

![Graph](image_url)  

Fig. 16. Typical pressure-time responses in a saturated piezocone and the reference transducer in the calibration chamber.

In some cases, however, less satisfactory responses are obtained. The curves shown in Fig. 17 were obtained from a commercial cone where the designer of the electronic system had incorporated an electronic filter in order to minimize the signal noise. This resulted in a time-lag of about 60 milliseconds at trapezoidal pressure changes and a reduced degree of response at shorter load impulses. Details of this kind are seldom given in the technical data supplied with the cone equipments and similar effects may occur if other less suitable electronic designs or components are used.

Another demand that is put on the measuring system is that it should have a very low volume change at a change in pressure. This property cannot normally be tested in this way, see Section 4.3.
Fig. 17. Example of time-lag and reduced degree of response due to an electronic filter, a) trapezoidal loading b) detail of the curve for a pressure increase c) relatively slow stress impulse.
4.3 Calibration of saturation

It has often been recommended to check the degree of saturation in filters and cavities in the cones by inserting them in a cell and measuring the response-time for pressure changes. This has been tried in the calibration chamber at the Swedish Geotechnical Institute and was found to be less useful. Independent of the method of saturation and of the pressure transmitting fluid used, the responses were direct and total. Only when both the filter and the cavities were completely dry, could a time-lag of 7-8 milliseconds be observed.

The filter had a medium pore size (about 20 µm) in the range of 2 to 120 µm that has been suggested by various researchers. The response-times could be increased somewhat for filters with smaller pore sizes but, even so, this does not seem to be a feasible way of estimating the degree of saturation.

The degree of saturation is of vital importance, however, both for keeping the cone saturated when passing unsaturated soil layers and when negative pore pressures occur, and for the ability to measure fast variations in the pore pressure. Unlike the situation in a calibration cell, the water in the soil is not free. A lack of saturation in the pore pressure measuring system (or a non-rigid measuring system) entails that water has to flow out of (or into) the soil whenever there is a change in pore pressure. This water flow, even if minute, causes a momentary stress change in the soil itself and the full initial pore pressure change cannot be measured within the available time unless the permeability in the soil is high. A calibration system that would simulate what is happening in the soil, and which would enable an evaluation of the degree of saturation and the stiffness of the measuring system, would therefore entail measuring responses to pressure changes at very restricted flows of the surrounding water. As far as is known, no such device has been developed.
4.4 Calibration of various pressure transmitting fluids

The requirements on the pressure transmitting fluid to be used in filters and cavities are mainly that it should be non-compressible and, as far as possible, retain saturation at negative pore pressures and when passing non-saturated soil layers. Three kinds of fluids are commonly used; water, glycerine and silicone oil. All three fluids have to be de-aerated before they are used.

Water has the advantages that it is readily available and can be de-aerated by boiling in the field. The results from field tests in soft soils are good, provided that the soil is predrilled down to the free ground water level, that the soil is saturated and that no negative pore pressures occur.

Glycerine and silicone oil are both excellent pressure transmitting fluids. They are de-aerated by vacuum and are both considered to retain saturation better than water. They also have the advantage over water in that they do not freeze until at extremely low temperatures. Glycerine is highly hygroscopic and is easily mixed with water, while silicone oil does not mix with water at all.

Glycerine and silicone oil are mainly used in order to better retain saturation at negative pore pressures and when passing unsaturated soil layers. This is aimed at improving the quality of the testing in stiff and unsaturated soils and, when completely successful, it makes testing more rational as preboring may then not be necessary.

The advantage of fluids that mix with water has been debated. At the Swedish Geotechnical Institute, a number of test series were performed in the calibration chamber in order to study the behaviour of the different fluids. In the first series, cones and filters were saturated with the different fluids and the response times were tested. In all cases the responses were total and direct.

The cones were then assembled with saturated filters but with dry cavities inside. In this case, water initially gave the best response. The response in the cone with glycerine rapidly improved with successive pressure changes. This may be attributed to the dilution of the viscous glycerine with water. The poorest response was obtained in the cone with silicone oil and the response did not improve significantly with further pressure impulses.

In another test series, the assembled and saturated cones were subjected to vacuum for one minute in the calibration chamber before the cell was water-filled and the response was tested. In this test, the cone with glycerine gave by far the best response and the response in the cone with silicone oil gave the poorest response, FIG. 18.
Fig. 18. Examples of pore pressure responses in piezocones after 1 minute of treatment with vacuum in dry calibration chambers; a) glycerine b) silicone oil.
At penetration in clay the filters become more or less clogged by finer particles. In order to simulate this, a test series was performed where the assembled cones were first inserted into a container with a slurry of organic clay, which according to previous experience has a strong tendency to clog filters. The slurry was then subjected to cycles of alternating vacuum and atmospheric pressure with each pressure lasting until the pressure inside the cone had responded. This procedure was repeated for half an hour. The cones were then taken up, scraped off and inserted into the calibration chamber. To enable an evaluation of the clogging effect, the cavities inside the cones were first emptied of fluid. The responses showed considerable clogging effects in the initially dry or water-saturated filters. Some, but much smaller, clogging effects could be observed for the cones with glycerine and silicone oil. Also in these tests, glycerine gave the best results and silicone oil the poorest.

From the results, it has been concluded that

- all fluids give excellent results when the cones are fully saturated
- glycerine seems to be best at keeping the saturation at negative pressures
- both glycerine and silicone oil diminish clogging effects
- silicone oil, which does not mix with water, seems to adhere to the solid particles in the filters and form a film around them. If any lack of saturation occurs in the cone and significant amounts of water are required to pass through the filter, then the silicone oil itself acts as a clogging of the filter and severely restricts the water flow and the response.

There are other aspects of the choice of pressure transmitting fluids, such as the gradual decay of the properties of glycerine when it becomes diluted with water. This may become significant at testing in deep water or in deep profiles with stiff or unsaturated soils. For testing on land in profiles with soft or medium stiff soils overlain by dry crust and possibly some stiffer layers, however, the results in the test series led to a recommendation to use glycerine or alternatively to use water in conjunction with predrilled and cased holes down to the free ground water level and through the stiff crust.
4.5 Remarks on demands on pore pressure response in relation to frequency of pore pressure readings

The demand for good saturation and fast pore pressure responses relates to the ability to obtain a detailed picture of the stratigraphy and especially to observe thin layers of silt and sand in clay and of clay in sand. In very careful tests in clay, it has even been possible to distinguish the character of the clay as clay, silty clay or varved clay. This has mainly been possible with the original pore pressure probe, where the results were registered on a strip chart recorder. The pen then registered the continuous analog signals and the paper feed was controlled by frequent pulses from the depth recorder on the pushing rig, FIG. 19.

Fig. 19. Example of results from pore pressure sounding. After Torstenson (1975).
When the pore pressure measurement was included in the piezocone, this ability to register variations in detail often disappeared. In order to keep the collected and stored amount of data down to a reasonable volume, readings are normally taken only at every 50 millimeters of penetration, which is normally sufficient when only tip resistance and sleeve friction are considered. In some cases, readings are actually taken more frequently but are then averaged over some length and only the average value is saved. Both procedures have similar devastating effects on the resolution as if large air bubbles had been introduced into the measuring system.

Some data acquisition systems use multi-channel strip chart recorders to enable the operator to follow the results during the test in a general way. The resolution of these charts is often so low that no further interpretation can be made from them.

This practice is inconsistent with the demands for pore pressure responses and quite unnecessarily eliminates the possibilities of obtaining detailed stratifications.

Most depth recorders have resolutions better than 10 mm and the data acquisition systems can read and store data very fast. There should also be no great problem in separating the readings of the pore pressure from the other data and using different storage routines if the amount of data has to be kept down. There is therefore no need to return to the strip chart recorders to regain most of the previous quality of results, but only a fairly simple reprogramming is required. This, however, has to be done to achieve consistency with the high demands for pore pressure responses.

4.6 Examples of pore pressure profiles obtained at different test procedures

The pore pressure profiles obtained in two piezocone tests with different equipments at the same location are shown in FIG. 20. With the first type of equipment, the pore pressure is recorded at every 8 mm of depth and in the standard version of the equipment the pore pressure readings for every depth interval of 50 mm are averaged and the average value is stored. With the other type of equipment, readings are normally taken only at every 50 mm of penetration. With the special version used at SGI, readings can be taken at every 5 mm of depth. The four pore pressure profiles obtained by the different procedures are shown in the figure.
Fig. 20. Pore pressure profiles obtained at different frequencies of readings and data processing, a) readings at every 5mm of depth, b) readings at every 8 mm of depth, c) readings at every 50 mm of depth and d) readings averaged for every 50 mm of depth.
Fig. 20. Cont.
The results in FIG. 20 clearly show that the detailed information on the soil variability obtained at high-frequency readings, where also the stop levels for addition of new rods can be easily identified, is more or less lost when the readings are taken at a low frequency or when the readings are averaged. Both reading at every 5 and every 8 mm of depth give the same information on stratigraphy as was previously obtained by the pore pressure sounding as illustrated by Torstensson (1975), but at less frequent readings the details gradually disappear.

FIG. 21 shows the pore pressure profiles obtained from two piezocone test at the same location with different testing procedures. In one test the dry crust was prebored and the hole was encased and filled with water. The cone and the filter were saturated with water and carefully lowered into the prebored hole. In the other test, glycerine was used as the pressure transmitting fluid and the test started from the ground surface without any preboring.
Fig. 21. Pore pressure profiles obtained in comparative piezocone tests, one with preboring and water and the other with no preboring and glycerine.
The results in FIG. 21 indicate that in soft clay profiles with limited crusts very similar pore pressures are often measured in tests without preboring and with glycerine in the tip compared to tests with preboring and water in the tip. Any differences are mainly associated with the inhomogeneous layer directly below the clay crust, which is affected by both the closeness to the ground surface, (weathering), and by root threads.

In the first profile, negative pore pressures were measured in the sounding without preboring down to a depth of 1.3 m and full positive pressures were obtained at 2 m depth. In the prebored test, the pore pressure rose directly to full positive pressure at 1.2 m depth. In the next profile, negative pore pressures were recorded at both soundings at a depth of 1 metre. Thereafter the pressure in the tip with glycerine rose to full positive pressure at a depth of 1.3 metres, whereas full pressure in the tip with water was not reached until at 3 m depth. Such irregularities were observed in a number of tests and seem to be related to the inhomogeneity in the upper soil and to insufficient preboring. In those cases where negative pore pressures developed in the tips with water, the pore pressures in general seemed to return more slowly than in tips with glycerine.
5. CALIBRATION OF TEMPERATURE EFFECTS

5.1 Equipment

The equipment required for calibration of the temperature effects is very simple. It consists only of a water bath large enough to accommodate the cone, a thermometer and an arrangement of the equipment so that readings of all channels can be taken versus time. For normal Swedish conditions, it is usually of interest only to calibrate the temperature effects between 0°C and 30°C and these temperatures can easily be obtained in the water bath by use of regulated tap water and some ice. When using glycerine or silicone oil in the cones, the temperatures may actually be lower than 0°C without damaging the equipment. Calibration at lower temperatures, however, involves many problems and the measured temperature effects on the cones can, if necessary, be extrapolated.

Readings of the temperature effects versus time are easily obtained by rotation of the depth recorder wheel in the sounding equipment at a constant rate or by rotating it at certain time intervals.

5.2 Change in zero readings after stabilization of temperatures

In the investigation by Lunne et al (1986) it was shown that the main thermal effects on the cone calibrations consisted of shifts in the zero readings at a change in temperature. This change is fairly linear with temperature and can be expressed in kPa/°C. The zero shifts were demonstrated to be related to the measuring range of the cones in that they increased with increasing measuring ranges. There was also a great difference between cones where the manufacturer had tried to compensate for temperature effects and cones where this had been neglected.

The measured zero shifts ranged from extreme values of 30 kPa/°C for the tip resistance and 1 kPa/°C for the friction sleeve to average values of 7.5 kPa/°C and 0.4 kPa/°C respectively. The best values for 5 ton cones were in the order of 2 kPa/°C for the tip resistance and 0.08 kPa/°C for the sleeve friction. Even better results for the tip resistance were obtained by a special cone design where the pressure was measured by a commercial high quality pressure transducer.
In general, these values have improved since the importance of temperature compensation has been stressed, but there are still cones with very poor temperature stability. The temperature compensation can never be perfect and it has to be checked.

At SGI a number of cones were specially ordered from different manufacturers with high demands on the temperature stability. The typical zero shifts for these cones are shown in TABLE 2.

**Table 2. Calibrated zero shifts in the range of 0-30°C for temperature compensated cones.**

<table>
<thead>
<tr>
<th>Measuring range</th>
<th>Tip resistance</th>
<th>Friction sleeve</th>
<th>Pore pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 ton</td>
<td>1-2</td>
<td>0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>0.5 ton</td>
<td>0.23</td>
<td>0.04</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The values in TABLE 2 correspond for 5-ton cones to the best values obtained by Lunne et al. 1986 and indicate a level that could be demanded for such cones with one exception. The value for the pore pressure transducer is much higher than expected. It should be in the same order as for the low range cone since the pressure ranges for pore pressure are about the same. It is also too high in relation to what is normally obtained for commercial high quality pressure transducers in this range. This may depend on the transducer itself or on its installation in the cone. The error may seem small in relation to the dynamic pore pressures that are measured at penetration in fine grained soils, but very high demands have to be put on the stability of the transducer as it is also used to measure the stable in-situ conditions in more permeable layers.

The temperature stability in the low range cone is, as expected, improved in about the same order as the range is lowered. In this cone only the range of the tip resistance has been reduced and the measuring ranges for the sleeve friction and the pore pressure are about the same as for the 5-ton cones.

The calibration is performed in such way that the cone is stabilized for a temperature in a water bath and the zero readings are taken. The cone is then transferred to a second water bath with another temperature and readings of the output signals and the temperature in the bath are taken until they are stabilized. This stabilization
typically takes about 10 minutes. When the cone is lowered into a water bath also the effects of the water pressure on the readings of the various transducers have to be taken into account. It is therefore advantageous to use identical water baths and positions of the cones at zero-readings and at stabilization for new temperatures. Otherwise the pore pressure effects have to be estimated and accounted for.

5.3 Calibration of effects of temperature gradients

During the stabilization of the cone for a change in external temperature there are temperature gradients in the cone which affect the readings of the transducers. This often results in transient responses that can reach large negative and positive values during the same stabilization process, FIG. 22.

![Fig. 22. Transducer signals during equalization of a sudden temperature change in the cone.](image-url)
This phenomenon make it important to follow the outputs of the transducers during the time for stabilization so that the maximum errors can be evaluated. For sudden temperature changes they are typically in the order of 2-3 times the permanent zero shifts.

These transient processes also make it impossible to correct for sudden temperature changes even if the temperature is measured inside the cones.

5.4 Calibration of other temperature effects

Apart from the cone itself, there may be other parts of the measuring system that are affected by temperature. Normally, they should be designed and set up in such a way that they are not affected by the outside temperature. In some cases, however, it cannot be avoided that long cables or other electrical components are exposed to rather large temperature variations. An evaluation of these effects can be made by comparative calibrations in room temperature and in field conditions, either at the site or simulated in temperature controlled rooms in the laboratory.

Also the mechanical parts of the system may have to be checked for temperature effects. For example, it was found that for one equipment there was a difference in depth registration between summer and winter conditions in Sweden. The difference was significant (> 1%) and could largely be attributed to a fairly large coefficient of expansion in the hard-rubber wheel used for depth recording.

5.5 Examples of temperature effects on results from soundings

Examples of the temperature effects on the results from penetration tests with different cones were presented by Lunne et al (1986), FIG. 23.

Another striking example of the differences that can be obtained at piezocone tests in clay with poorly temperature compensated cones was shown by Konrad (1987), FIG. 24.

The figure shows the results of two parallel tests; one with the zero readings taken at an air temperature of 30°C and then sounding through the crust and one with the zero readings taken after stabilization for about 20 minutes in the water in a predrilled hole through the crust (at 6-10°C).
Fig. 23. Comparison between tip resistances obtained in penetration tests with zero values taken at different temperatures. From Lunne et al. 1986.

Fig. 24. Results from two parallel penetration tests with different temperatures when taking zero-readings. (From Konrad 1987)
The error can be diminished by the rather laborious and time consuming procedure of predrilling and casing a hole, letting it fill with ground water or filling it with water of the right temperature and letting the cone stabilize before the zero-readings are taken. Even so, it is obvious that the confidence level in the results from tests in soft soils with a cone with this type of properties must be very low. All temperature variations simply cannot be avoided.

In FIG. 25, the results from tests with temperature compensated cones are shown.

The results show that the temperature is more or less stabilized at a penetration depth of about 6 m (with stops for addition of new rods). They also show that most of the temperature errors occur above this level, but permanent zero-shifts due to incorrect zero-readings may remain for the rest of the soundings.

The tests in FIG. 25 were performed with 5-ton cones with good temperature compensation (see TABLE 2). In the test series the cone temperatures were intentionally varied so that at the start of one sounding the cone was cold, at another it was warm and in the reference test the cone was kept close to the ground temperature. The effects are therefore exaggerated compared to conditions where care has been taken to keep the cone temperature at the right level, but they may be considered relevant for cases where this point has not been observed. In these latter cases, fairly large errors may be obtained also with cones with good temperature compensations.

It should also be observed that a certain temperature shift must always be expected and the demand for temperature stability must therefore be high even if care is taken to keep the cone temperature at the right level. Today, many cones have an internal thermometer which continuously records the temperature. This can be considered as a great help in ascertaining whether the demands for a relatively constant temperature are fulfilled.

In FIG. 25 only one reference test is shown, but there are many more available. It is therefore ascertained that the reference test results are relevant and that the normal scatter in test results is much smaller if care has been taken to keep the cone temperature at the right level, FIG. 26.
Fig. 25. Results from parallel penetration tests with temperature compensated cones and different temperatures when taking zero-readings.
Norrköping

Fig. 25. Cont.
Fig. 26. Results from parallel soundings with start at ground temperature.
Fig. 26. Cont.
6. CALIBRATION OF SEISMIC CONES

Seismic cones do not normally have to be calibrated, but the output signals can be evaluated on the basis of the calibration charts for the commercial transducers and read-out instruments that are used. In the most common use of the seismic cone, which is evaluation of the initial shear modulus in the soil, the signals are not even evaluated but only the times of their arrival are measured. Sometimes, however, it is of interest to analyse the signals, e.g. to be able to estimate the magnitude of the shear strains in the test. As mentioned above, this should be possible on the basis on technical data supplied with the equipment.

If, for some reason, the available information is inadequate or has to be checked, the seismic system can be calibrated in the laboratory. This requires access to a precisely regulated vibration source where the cone can be accommodated.

Such a need for calibration occurred at SGI when a complete seismic cone equipment was delivered with excellent instructions on how to operate and evaluate the times for arrival of the shear waves, but without any information on the data for, or make of, the seismic transducer or what the units on the axis for the seismic signal on the built-in oscilloscope indicated.

The system was calibrated in the electronics workshop and it was then found that the output for the transducer was linear for velocities between $\pm 2 \text{ mm/s}$. The maximum range (full scale) of the oscilloscope corresponded to a velocity of $\pm 1 \text{ mm/s}$ and the signal within the range of the oscilloscope was thereby also linear. This is the type of information required and which should preferably be supplied with the equipments.
7. REFERENCES


The Swedish Geotechnical Institute is a government agency dealing with geotechnical research, information and consultancy. The purpose of the Institute is to achieve better techniques, safety and economy by the correct application of geotechnical knowledge in the building process.

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