FIELD COMPRESSOMETER-PRINCIPLES AND APPLICATIONS

COMPRESSOMETRE DE CHANTIER-PRINCIPES ET APPLICATIONS

ПОЛЕВОЙ КОМПРЕССИОМЕТР – ПРИНЦИП И ПРИМЕНЕНИЕ

N. JANBU, Professor, Norwegian Institute of Technology, Trondheim
K. SENNESET, Chief Engineer, Norway

SYNOPSIS. A field instrument for in situ determination of the modulus number and the coefficient of consolidation of soil sediments was developed in 1965-66. The instrument has been tested out over a 5 year period on research and consulting jobs, and it is now available for practice.

This paper gives a short describtion of the theoretical principles involved, and derives thereof interpretation procedures to be applied to the field observations. A short describtion is also given of the instrument itself and the test procedure. The results obtained are examplified by means of parameter - depth profiles for two sites, the maximum depth being 27 meters.

Although the experiences gained so far are limited to silt and sand deposits, they have clearly demonstrated the practical usefulness of the field compressometer. Programs are now being planned to investigate new fields of application.

INTRODUCTION

A settlement prediction in practice usually involves a forecast of expected total settlement, and an estimate of the time rate of settlement. The forecast of the total settlement requires as a minimum one stress-strain parameter for the soil (say a tangent modulus) while the time rate analysis requires at least one time-settlement parameter (coefficient of consolidation). Both these parameteres (or set of parameteres) depend at least on stress and stress history and on type of soil. Moreover, the parameteres for remoulded soils are often very far from real in situ soil conditions. Therefore, a major requirement for successful practical applications is that the proper soil parameteres should be obtained for in situ conditions or as nearly field conditions as possible.

For clays and clayey soils it is possible to obtain and install test samples that are relatively undisturbed. And, although it is very difficult to reproduce the correct in situ state of stress and strain, the modern soil sampling, testing and interpretation procedures may lead to relatively dependable engineering parameteres for predecting settlements in clayey soils. Moreover, since most settlement forecasts in practice are one-directional, the corresponding soil parameters are obtained from one-dimensional tests, for instance in oedometers.

In order to obtain oedometre data, however, soil sampling and laboratory testing operations are required. When it comes to sandy soils it is next to impossible to extrude undisturbed samples for laboratory testing. Therefore, it is highly desireable to be able to obtain in situ measurements of the settlement parameters of sandy sediments. Moreover, the ideal aim would be to measure the same parameters that now are used in practical settlement analysis based on oedometer tests.

Therefore, a theoretical solution was first obtained for the settlement of a circular plate placed at an arbitrary depth below ground surface. The concept of tangent modulus and soil adopted stress distribution was used for the derivation of the settlement formula, containing the modulus number. Similarly a time rate solution was adopted containing the coefficient of consolidation.

The theoretical solutions then initiated the development of the compressometer, and the solutions are now used for interpretation of the field observations, leading to depth profiles of moduli, and coefficients of consolidation.

THEORETICAL PRINCIPLES

For the purpose of illustrating the theoretical principles involved in the determination of in situ modulus by the field compressometer reference is made to Fig. 1.

A circular plate is installed at a depth where the effective overburden is equal to p_o'. The plate is being loaded stepwise, and each load step stays long enough to complete the consolidation process. A load settlement curve (p'-δ) is indicated in principle in the figure.

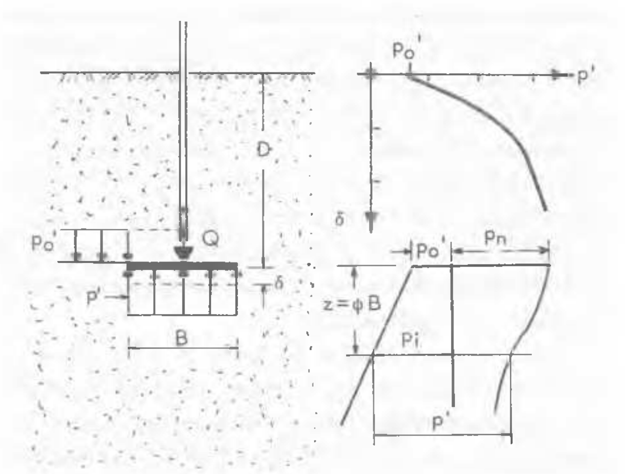


Fig. 1. Settlement of a circular plate in the interior of a soil sediment. Key sketch.

For normally consolidated soils, in which $p_o' = p_c'$, one must expect that the settlement in the virgin compression part ($p' > p_o'$) must in general be a function of effective overburden p_o' net load increase, $p_n = p' = p_o'$, the diameter of the plate B, and the soil modulus M.

If one considers a sandwich of width B and thickness dz at an arbitrary depth z below the plate one can state that the change of thickness equals $d\delta = \varepsilon dz$, where $\varepsilon = \int dp'/M$. Here dp' = vertical effective stress increase, and M = one-directional soil modulus for the actual state of stress, and ε = vertical strain. The settlement δ of the plate is then obtained by summing upp all $d\delta$, hence.

$$\delta = \int_z \varepsilon dz = \int_z \left(\int_\sigma \frac{dp'}{M}\right) dz \qquad (1)$$

The integration over depth z goes from 0 to ∞ (or rather to vanishing strain ε) while the integration over effective stress σ runs from p_i' until p'.

Eq. (1) demonstrates that in theory there are two basic problems that have to be solved, namely the stress distribution p' with depth and the formulation of one-directional moduli as function of stress for various soil sediments. Both problems have been subject of intensified studies in a number of thesis and research reports at our institute over the least 12 years. It is therefore felt that these problems are now adequately resolved for practical purposes.

When the stress distribution and the modulus dependency are obtained, the integration can be performed, and a closed formula for δ was thus derived. It reads:

$$\delta = \frac{S}{m} \frac{p_n B}{p_a} \qquad (2)$$

in which

$p_n = p - p_o'$ = net load on plate
B = plate diameter
p_a = reference stress = 10 t/m² ∿1 atm.
S = dimensionsless settlement number
m = modulus number

The modulus number is defined in the idealized stress formulation of one-directional moduli, Janbu (1963),

$$M = mp_a \left|\frac{p'}{p_a}\right|^{1-a} \qquad (3)$$

where a = stress exponent.
When combining Eqs (1), (2) and (3) one finds that

$$S = \frac{p_a}{ap_n}\int_0^{\infty}(f^a - f_i^{\,a})\,d\psi \qquad (4)$$

where

$$f = p'/p_a \qquad f_i = p_i'/p_a$$

are functions of the dimensionless depth $\psi = z/B$.
The result of the integration for a = 1, ½ and 0 are plotted in three diagrams in Fig.2:

(1) For a = 1, corresponding to a constant modulus $M = mp_a$, the value of S is roughly constant and equal to $S \sim 0.72$, except perhaps very near the soil surface. The constant modulus concept is a fair approximation for overconsolidated clays, and for undrained, initial conditions in saturated clays.

(2) For a = ½, corresponding to a modulus $M = m\sqrt{p'p_a}$ one finds that S drops with increasing p_o' and p_n. This square root modulus approximates to a fair degree sandy and silty sediments. The modulus number may run from less than 50 up to several hundreds.

(3) For a = 0, in which case M = mp', the decrease of S for increasing p_o' is more pronounced, but otherwise the general trend is as shown for case (2). This linear modulus is a good approximation for normally consolidated, saturated clay and very fine silt. The modulus number may vary from 5 up towards 50.

By means of Fig. 2 and Eq. (2) one can readily obtain the field value of the modulus number m for a soil deposit when the relationship between p_n and δ are obtained by field measurements down through the deposit.

Similarly, one can obtain the coefficient of consolidation from time - settlement observations in the field by utilizing the defining equation for dimensionless time in the onedimensional or axisymmetric consolidation theories.

In principle, the basic equation reads

$$c = T\,\frac{d^2}{t} \qquad (5)$$

where

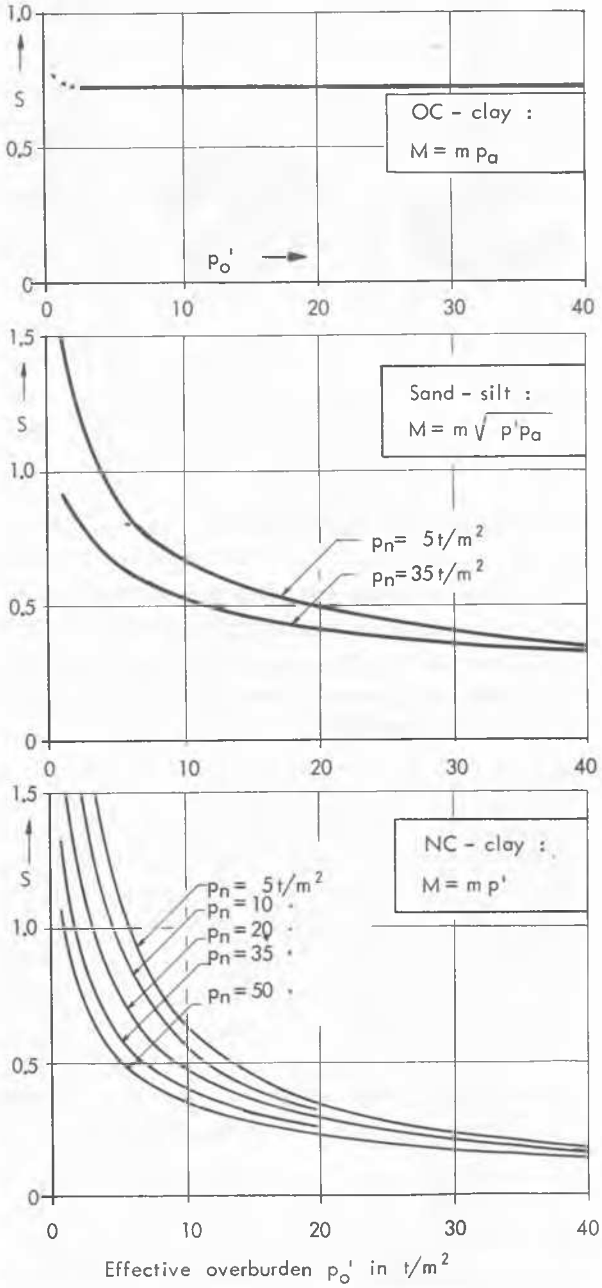


Fig. 2. Settlement number S as function of effective overburden p_o' and net load p_n for various soil moduli M.

c = coeff. of consolidation
d = characteristic drainage path
T = dimensionless time factor corresponding to the degree of consolitation obtained at time t,
t = time after load increase

For the compressometer radial drainage will usually dominate, hence it measures essentially c_r. Therefore, the characteristic drainage path may for convenience be taken as the plate radius, ie d = R. Under these circumstances, the objectives of our theoretical studies has been to obtain adequate correlations between degree of consolidation and time factor for analytical models that simulate the actual conditions to the best possible degree. The result of these investigation is given below.

INTERPRETATION PROCEDURES

The final results of the diverse theoretical studies have lead to the derivation of standard interpretation procedures for obtaining the coefficient of consolidation, and the modulus number, once the field load test data are available.

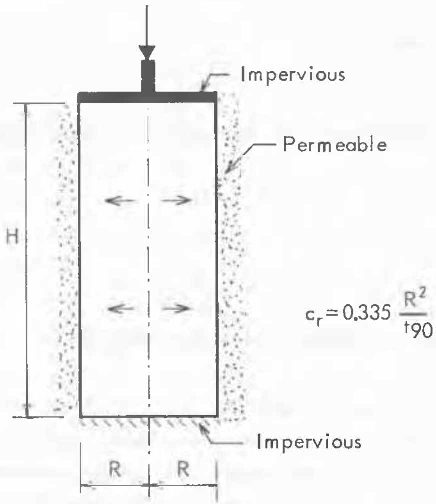
Coefficient of consolidation

For each load increment the settlement is plotted versus square root of time, see Fig. 3. As a rule the first part of this curve is linear, and it intersects the settlement axis at the theoretical zero reading. From this zero point a straight line with relative inclination 1.3:1 is constructed. It intersects the test curve at approximately 90% primary consolidation, and the corresponding time t_{90} is obtained, whereafter

$$c_r = T_{90} \frac{R^2}{t_{90}} = 0.335 \frac{R^2}{t_{90}} \qquad (6)$$

in which

c_r = coeff. of radial consolidation
R = ½B = plate radius
t_{90} = time of 90% consolidation
T_{90} = 0.335 = time factor for 90% consol.



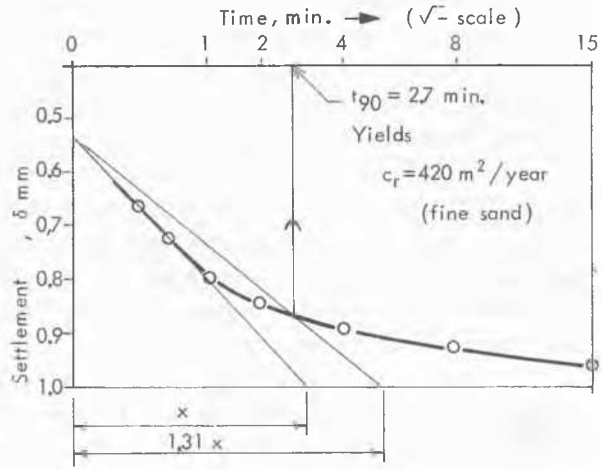


Fig. 3. Analytical model for the determination of c_r with an example from a field test in fine sand. (Drammen)

This interpretation procedure was established after studying idealized models with axial and radial drainage, Mc Kinley (1961), and after having performed a number of comparative analysis and tests, Enlid (1970).

For the example in Fig. 3 it was found that t_{90} = 2.7 min. The plate diameter was 16 cm, hence c_r = 8 cm²/min. = 420 m²/year. The soil was slighty organic fine sand.

Modulus number

For each depth a load (p') settlement (δ) curve is drawn to an arithmetic scale. The in situ overburden p_o' is marked off and from this point a secant or tangent is drawn through the observation points over the required net load p_n, and the corresponding value of δ is thus determined, see Fig. 4.

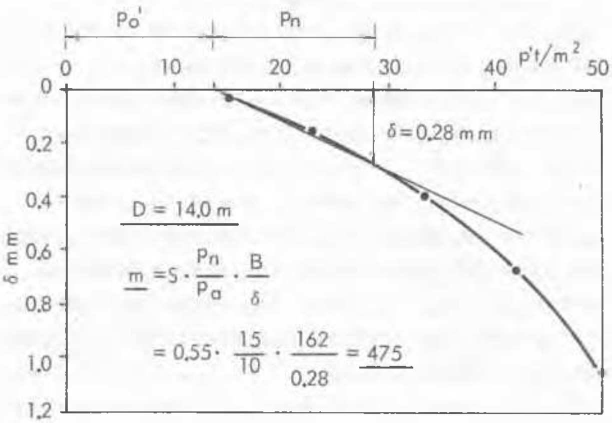


Fig. 4. Determination of the modulus number from obtained load settlement curve. Example, dense sand, Drammen.

From these data (p_n and δ) one can calculate the modulus number, m, from Eq. (2):

$$m = S \frac{p_n B}{p_a \delta} \qquad (7)$$

Here, the settlement number S must be obtained from Fig. 2 for the appropriate modulus. For sandy soil the square root modulus is used.

The example shown in Fig. 4 used a plate with diameter B = 162 mm (area = 200 cm²). Test depth $\sim$ 14 m corresponding to $p_o' \sim 14$ t/m² where a layer of dense sand was encountered. For $p_n = 15$ t/m² the settlement increase $\delta = 0.28$ mm. The middle diagram in Fig. 2 yields S = 0.55 for $p_o' \sim 14$ t/m and $p_n = 15$ t/m². Eq. (5) will then lead to m = 475, which is a normal value for dense sand.

THE INSTRUMENT

The field compressometer is in principle a bearing plate equipment where the bearing plate itself is formed as a screw plate. It

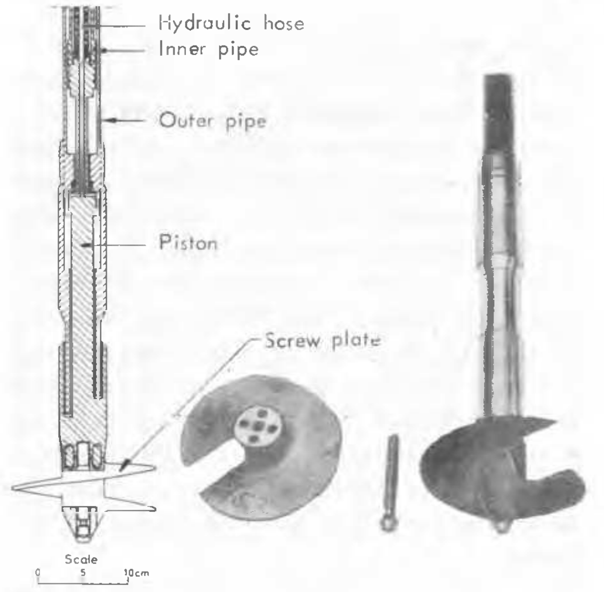


Fig. 5. The field compressometer

can be screwed down to a specified depth either by ordinary drilling equipment or by hand. At each selected depth a load test is performed.

Besides the screw plate the compressometer consists of a hydraulic jack, to which the screw plate is connected. The hydraulic jack is fixed to a system of pipes which forms the connecting string to the ground surface. In Fig. 5 is shown the cross-section of the compressometer. The figure also shows photos of a screw plate, the center rod which connects the plate to the jack, and a general view of the compressometer. The screw plate has a rise of about 4.5 cm. The most common diameter is about 16 cm, corresponding to a loading area of 200 cm². The material is usually cast iron, which allows for flexible design and inexpensive manufacturing.

The screw plate is fixed to the piston of the jack by a center screw, while four steel pins slide into the plate to resist torsional forces.

The jack is connected to an outer pipe system which will transmit both the external forces during installation, and the reaction forces during load testing. The oil pressure is transmitted to the jack through a hydraulic hose placed in the inner pipe system.

Fig. 5 shows that this pipe is directly fixed to the piston, and thereby to the bearing plate. Every movement of this plate can hence be observed on the soil surface. During installation of the compressometer the outer and inner pipes are firmly connected, locking the jack in its inner position. In that position it can take torsional forces. The necessary installation forces may usually be establisted by means of a drilling rig or a couple of men turning a convenient handle at the top of the outer pipes. When the bearing plate has reached the depth where the load test is to be performed the connection between the outer and the inner pipe is released.

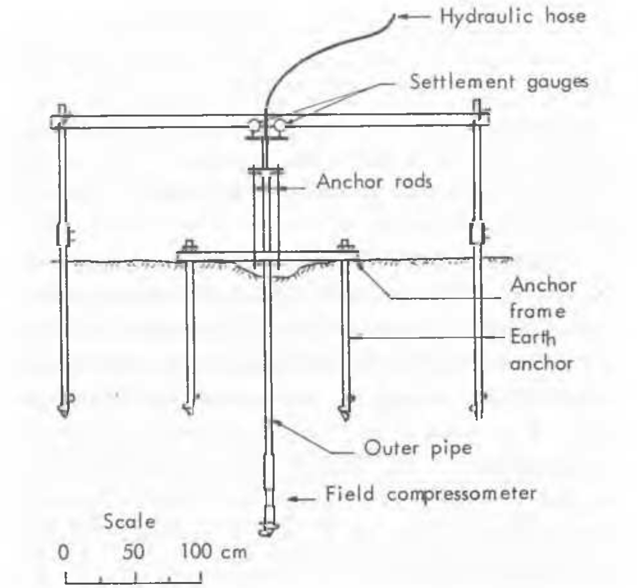


Fig. 6. Field arrangements during measurements of load - settlement and settlement - time curves.

tual load test are shown schematically in Fig. 6. The reaction forces during loading is taken up by the anchor frame (with four earth anchors) and by skin friction along the outer pipe. The settlement gauges are fixed to an independent, anchored beam. (In case a drilling rig is used, the anchor arrangements can be replaced by a connection to the rig, provided the rig is heavy enough.)

To establish the hydraulic pressure a container of compressed nitrogen gas is used. A pressure accumulator keep constant pressure during each load step. The applied gas pressure is controlled by a precision manometer.

TEST PROCEDURE

For any given depth of investigation, the test procedure is usually as follows:

(a) The first load step is chosen nearly equal to the effective overburden, p_o'.

(b) The settlement caused by each step is recorded either continually, or at selected time intervals. The time - settlement curve for each step or typical steps is usually plotted in the field on a square root scale, and the 90% consolidation is determined as shown in Fig. 3. Thus the final decision on the total time needed for the load steps can be made in the field.

(c) The load is increased step by step, and a time-settlement curve is obtained for each step. The maximum load which is actually applied at any depth can either be limited by bearing capacity failure, by the capacity of the instrument (100 t/m^2 for a 200 cm^2 plate) or by the maximum applicable stress range for the actual job, say $p' \leqq 50$ t/m^2.

(d) When the entire load test is completed at a given depth, the beam with the settlement gauges is removed. The jack is now locked in its inner position again by means of the double pipe system. The compressometer is then screwed down to the next depth of investigation.

The vertical distance between each load test is usually 1 meter, exceptionally as low as 0.75 m. For deep homogeneous deposits load tests at 2 to 3 meters intervals have been used. Successful measurements have so far been made to a maximum depth of 30 meters in fine sand deposits at the shores of the Trondheim Fjord.

The total time required to complete the compressometer measurements for one borehole depends of course on a number of interrelated factors, such as type of soil, number of load steps at each depth, number of depth readings,

and total depth. Assuming 5 load steps at each depth in a fine, inorganic sand, where each step must be kept 10 minutes to complete primary consolidation, roughly 8 depth measurements are completed pr. day.
This corresponds to a capacity of 8 to 15 m per day, for 1m to 2m vertical spacings between each test series.
In stratified soil one may have to pass through dense gravelly sand layers. In such cases the present equipment may be strained beyond its capacity. To avoid complications in such cases it is recommended to drill through these hard layers.

Since each screw plate is relatively inexpensive it has been found economical to leave it in the ground at the last depth of investigation. To make this possible the centre rod (which fixes the plate to the jack) has a weakened crossection permitting the rod to be snapped off by pulling. Thus the equipment can be pulled rapidly out of the borehole.

COMPRESSOMETER PROFILES

The load tests at each depth lead to modulus numbers (m) and coefficients of consolidation (c_r). These parameters are usually obtained for the actual stress range (or the net load p_n) whenever known at the time of the site investigation. The measured values of m and c_r are usually plotted versus depth. Examples of such compressometer profiles are shown in Fig. 7 and 8.
Fig. 7 summarises the results obtained by the field compressometer in a 10 meter thick clayey silt deposit overlain by 2.5 m of dense, semented sand. For comparision the results obtained by standard oedometer tests are included in the figure. For the oedometertests relatively undisturbed silt samples were obtained by the NGI-54mm thin walled tube sampler. The compressometer and the oedometer results agree well, except that $c_r > c_v$ for depths greater than 8 meters. By means of the data shown in Fig. 7 it was possible to predict the actual settlement of the school building, both in total amount and in time rate within ± 15%.

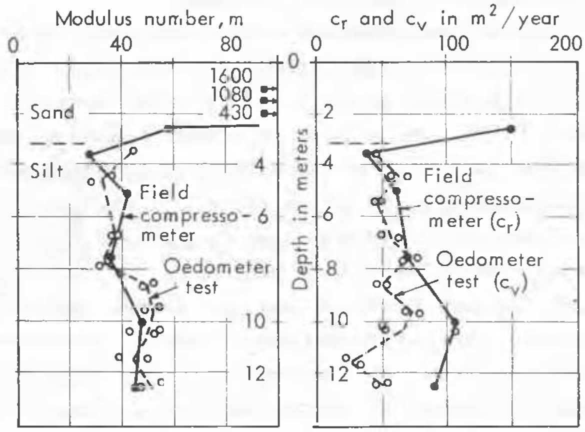


Fig. 7. Field compressometer results.
Silt deposit in Stjørdal.

In Fig. 8 are shown the results obtained down to 27 meters in a silty, fine sand deposit overlain by 6 m of hydraulically placed sandy fill. Since sampling was possible in the natural sediment, routine oedometer test results for modulus numbers are also included, and compare well with the compressometer results. Because of the rapid consolidation of the laboratory samples the standard oedometer tests could not yield c_v- values for comparison. The data shown in the figure are used in the foundation design of a heavy silo to be built on the site.

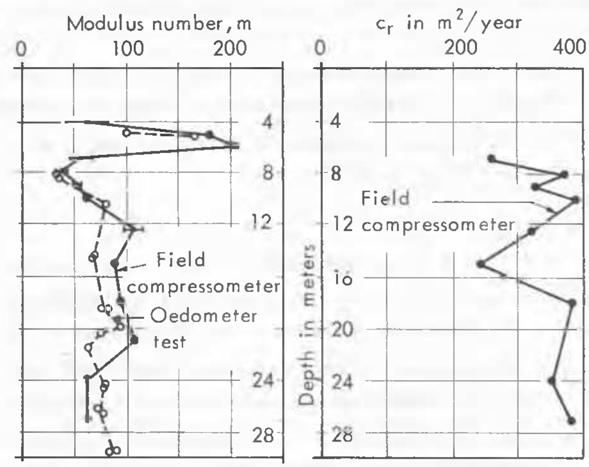


Fig. 8. Field compressometer results.
Sand deposit in Steinkjer.

EXPERIENCES. NEW APPLICATIONS

So far the compressometer have been used in practice in connection with the prediction of settlements in sand and silt for three test fills, one silo, one school building, one bridge, and at two sites for large industrial developments. Prior to these practial applications the instrument was tested out in several limited research projects.

This initial research and the actual application of the instrument have clearly demonstrated the practical usefulness of the field compressometer in foundation engineering. For those five cases where predicted and observed settlements are now available good agreement has been obtained, say within ± 20% as a rule. The use of the field compressometer has until now been limited mainly to silt and sand.

On one occation, however, it was used sucessfully in clay to determine the undrained shear strength. This field of application is possible to expand. The advantage over the vane would be that possible anisotropy was (at least partly) included in the registered value of undrained shear strength. On the other hand remoulding of the clay may be more pronounced for the compressometer.

A program is underway to investigate the possibility of determinering the preconsolidation pressure in clay deposits by means of the field compressometer. The program is not carried far enough to enable specific statements.

The same goes for a program designed to investigate the usefulness of the compressometer for determining "strength" and deformation parameteres of peat layers.

SUMMARY

The field compressometer described herein is in principle a helicot screwplate mounted on a hydraulic jack unit. The instrument can be screwed down to the required depth of investigation manually or mechanically. Load tests performed at a given depth will, by proper interpretation, give field values of the vertical (onedimensional) compression modulus, and field values for the coefficient of radial consolidation. Thus the field compressometer can render depth profiles for these parameteres which are required in subsequent settlement analyses. The model and full-scale experiences which are gained up to now in sand and silty sediments appears to be very promising. Moreover, investigations are under way to explore new fields of application for the compressometer.

ACKNOWLEDGEMENT

The authors are greatly indepted to the firm of Ottar Kummeneje, and to the Road Laboratory for their interest and active participation in testing the equipment on actual jobs. Much credit is also due to the following engineers for the valuable research they carried out in connection with their diploma thesis: R. Hauan (1967), B. Haavardsholm (1967), Ø. Berle (1968), D. Fremstad (1968) and E. Enlid (1970).

REFERENCES

Enlid, E.(1970):"A theoretical and experimentel investigation of the usefulness of the field compressometer for determinering deformation parameters". Diploma thesis, in Norwegian. NTH, Trondheim.

Janbu, N.(1967):"Settlement calculations based on the tangent modulus concept" (3 guest lectures at Moscow State University) Bulletin No.2. Soil Mechanics, NTH, Trondheim.

Janbu, N.(1970):"Grunnlag i geoteknikk" (Fundamentals of geotechnique) Textbook, Chapter 4, pp 141-243, Tapir Forlag, NTH, Trondheim.

Kummeneje, O.(1956):"Fundamentering av oljetank i Drammen". NGI.publ. nr.12,Oslo. (First use of screw plate in Norway).

Mc.Kinley, D.G.(1961):"A laboratory study of rates of consolidation in clays with particular reference to conditions of radial pore water drainage". Proc.5. ICSMFE, Paris.