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IN SITU CREEP BEHAVIOUR OBTAINED FROM LONG-TERM SETTLEMENT OBSERVATIONS

LE COMPORTEMENT IN-SITU DU FLUAGE DES SOLS BASE SUR LES OBSERVATIONS DES TASSEMENT A LONG TERME

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SYNOPSIS: For large, high-cost projects it is of utmost importance to be able to predict how the settlement or ground subsidence will develop with time, during and after load application, or stress changes. Recent costly failures to predict properly the timerate due to large stress changes in various sediments have underscored the necessity for improving the state of art in this field.

This paper presents a simple method of back-calculation for evaluating the behaviour of the subsoil. It is applied to eleven case records, including the Gullfaks C platform in the North Sea, and the Kansai International Airport in Osaka. It appears that we may rapidly improve our ability to predict particularly the long-term settlement rates, by collecting statistical data from several more case records analysed in this same way.

INTRODUCTION

The purpose of this paper is to show by examples how one can utilize available case records of settlement versus time to back-analyse fundamental parameters of sediment behaviour. Herein, the main emphasize is on creep behaviour.

When the settlement (δ) is recorded with time (t) after load application (q) an informative diagnosis of such (δ - t) records can be made, using a very simple procedure, as follows:

Obtain the settlement rate $\dot{\delta} = \Delta\delta/\Delta t$ and plot the result along the time axis.

Calculate the settlement potential

$$S = \dot{\delta} t \tag{1}$$

and plot S along the time axis, see key sketches in Fig.1.

In the ideal, classical case, with a uniform load on a clay layer of thickness H , the ideal S - t curve should be parabolic to begin with, and gradually approach a constant value, S_e , where

$$S_e = \frac{H}{r_c} = \text{creep potential} \tag{2}$$

Here r_c = creep number, or time resistance number, Janbu (1969).

Today a large number of statistical data of r_c are available from oedometer tests on a variety of sediments. For saturated NC-clays conventional values of r_c may range from 30 to about 250 for water contents from 100% to 30%. For overconsolidated clays r_c is much larger, say > 400.

Today very few data are available of field values of back-calculated creep potentials, and in situ creep numbers, except for the 16 case records covered by Janbu et al (1989). In this paper 11 more case records are evaluated.

BUILDINGS ON MEDIUM CLAYS

In situ settlement potentials have been obtained for 4 Norwegian buildings on medium clays. Three of these records from Drammen were published by Bjerrum (1967), namely: Tumhallen, heavy and light part (TH.H and TH.L) and Konnerudgate 16 (K.16).

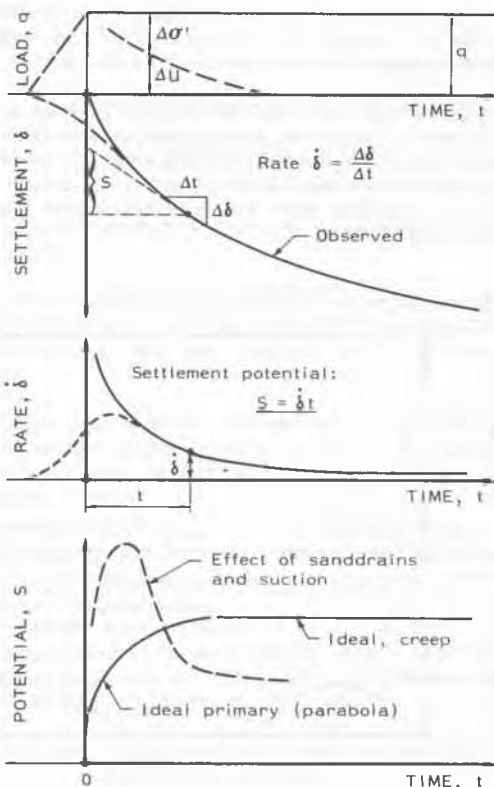


Fig.1 Definition of settlement potential

The fourth record was published by Andersen et al (1975) regarding Oslo Jernbanetollsted (OJT). This last record (OJT) was recently discussed by Janbu (1991).

The calculated potentials are plotted versus time in Fig.2. The most striking impression is that S_c remains fairly constant over several decades, while the parabolic shape lasts only 3 to 8 years.

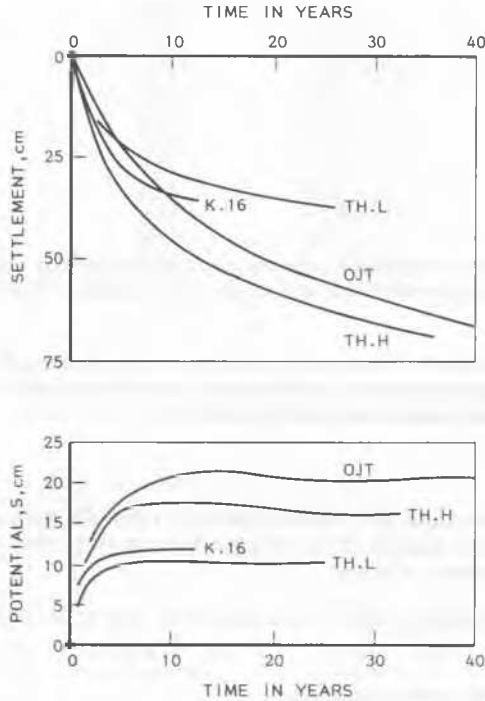


Fig.2. Settlement potentials for 4 buildings on medium clay

The figure shows that the back-analysed field values of the average S_c vary between 10 cm and 20 cm. The total layer thicknesses H are 25 to 36 m. The average field value of the creep number is now obtained from Eq.(2) as

$$\bar{r}_c = \frac{H}{S_c} \quad (3)$$

leading to in situ values of r_c between 150 and 250. This compares well with oedometer test results for these Norwegian clay deposits with water contents of 30 to 50%, and load/strength ratios of $q_v/s_v = 1.5-3.5 < N_c$.

The parabolic S-t shape during the early part of the records should indicate primary consolidation, according to the classical theory of consolidation. The parabola should then terminate at t_{50} , where

$$t_{50} = 0.2 \frac{d^2}{c_v} \quad (4)$$

when d = effective drainage path (seldom known).

The oedometer value of c_v runs between 10 and 15 $m^2/year$. Assuming double drainage, with constant strain over the full height one gets $t_{50} = 2-3$ years for K.16, TH.H and TH.L, and $t_{50} = 4-8$ years for OJT. The observed behaviour in Fig.2 shows that the parabolic shape terminates at approximately t_{50} assuming double drainage. Hence the creep behaviour starts to dominate already in the very early part of the primary phase.

THE GRAVITY PLATFORM GULLFAKS C

The large gravity platform Gullfaks C was installed at 220 m depth in the North Sea in May 1989. It is heavily instrumented and its behaviour has been very closely registered both during installation and continuously thereafter. The foundation design and the subsoil conditions are widely published, say in Boss'88 and Boss'92, Tjeltna et al (1992).

From the observed settlement versus time during the 3 years of existence, the settlement potential has been calculated in great detail, from the continuous record of deformation, Fig.3.

During the first 100 days after installation a suction of 300 kPa was applied (-30 m of water pressure). During that period the total settlement was 50 cm, and occurred for an almost constant settlement potential of 20 cm \pm 10 to 15%. Already in 1986 this potential was estimated at 16-24 cm from laboratory values of r_c .

During the next 265 days the suction was maintained at 100 kPa, and the average settlement potential over that period is seen to be 7 cm \pm 30%. For the next two years with no suction, the average settlement potential is 5 cm \pm 50%.

When going closely into the continuous records there is a lot of vital information yet to be digested. However, a few main trends can be focused on, regarding the variations in the settlement potential.

The 100 days with 300 kPa suction led to almost complete drainage of the upper 28 m of clay-sand including two embedded layers of soft to medium clay. The lower 10 m of clay was hardly effected. With $S = 20$ cm \pm it means that the corresponding average $r_c = 2800$ cm/20 cm = 140. The variation in S is small partly because of calm weather during the summer season.

For the two years with no suction the measurements have shown that it is primarily the lower 10 m of medium stiff clay that is now involved in the settlement. With $S = 5$ cm \pm and $H = 10$ m one finds $r_c = 200 \pm$, which is a very reasonable average for this clay with $w = 35\% \pm$ and $q_v/s_v \leq 3$.

During these last two years the S -value has fluctuated in average by $\pm 50\%$, but always so that S is lowest in the summer season (S) with calm weather, while the maximum values occur during winter (W) when high peaks are registered. This indicates that winter storms with repeated wave forces may have a cumulative strain effect, in the same manner as found by cyclic tests in the laboratory.

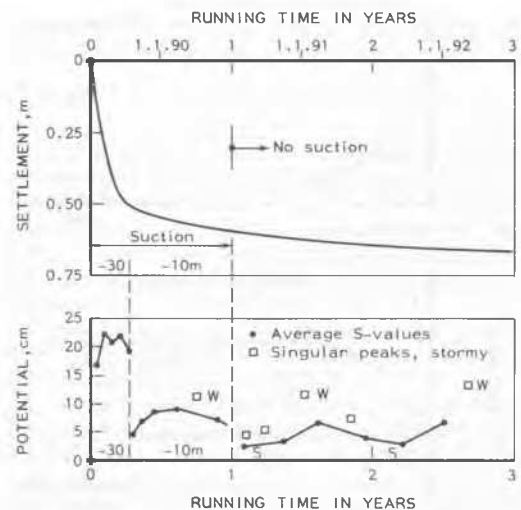


Fig.3. Settlement potential at Gullfaks C

TWO TEST FILLS ON VERY SOFT CLAYS

After the last world war Sweden was looking for a suitable site for a new airport. In Väsby and Skå-Edeby altogether 7 test fills were placed and their behaviour was recorded for about two decades. Here, one test fill from each site will be briefly reviewed, namely one at Väsby built in 1947, Chang (1969), and one at Skå-Edeby built in 1957, Hansbo (1960) and Holtz and Broms (1972). The details about the subsoil conditions and the construction of the two fills are found in the above references, and data extracts are also given by Nowacki (1973).

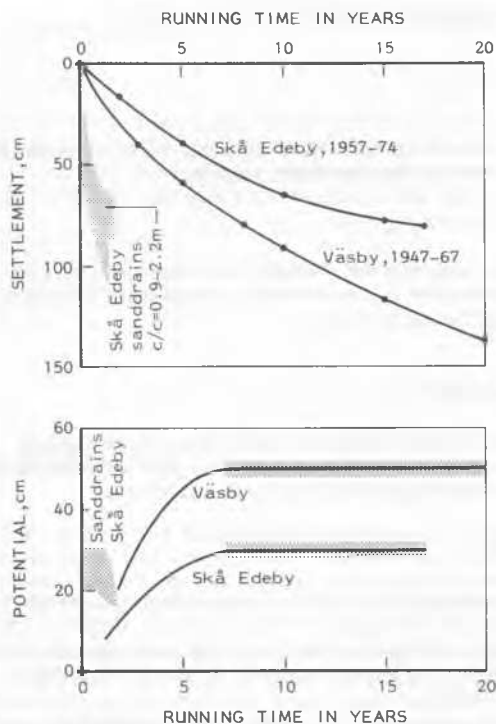


Fig.4. Settlement potentials for fills on soft clay without and with sanddrains

From the observed settlements versus time, the settlement potential is calculated, Fig.4. The S-t curves are almost ideal, with a parabolic shape during the first 6 years, and being constant the next 10 to 12 years of observation.

For the Väsby fill, a constant $S_c = 0.5$ m is found, corresponding to an average in situ creep number $r_c = H/S_c = 26$. This very low value is due to the large water contents (120-70%) and a fairly large undrained load/strength ratio of about 3.

For the Skå-Edeby fill a constant $S_c = 0.3$ m is obtained, leading to an average in situ creep number of $r_c = 40$, which is comparable to the above, because of lower water contents (85-50%) and a somewhat lower load/strength ratio of 2.6 in average.

In both cases the parabolic S-t curve ends after about 6 years. Formerly it was indicated that this state may correspond to 50% deformation assuming double drained layer, i.e. $t_{50} = 6$ years in the field.

Using Eq.(4) and $t_{50} = 6$ years one gets the following field values:

Skå-Edeby c_v	= 1.2 m ² /yr	(0.16 m ² /yr)
Väsby	= 1.4 m ² /yr	(0.60 m ² /yr)

The average laboratory values of c_v are given in paranthesis, according to data from Hansbo (1960) and Chang (1969), respectively, and Nowacki (1973).

This very large differences between the field and laboratory values of c_v can of course partly be due to lateral movements and lateral drainage in the field. However, that cannot be the whole explanation. There are reasons to believe that even the process during the first 6-7 years is not necessarily an hydrodynamic phenomenon alone, Janbu (1991).

These two case records from Sweden have long been famous for the observations that large excess pore pressures remained fairly constant ($\Delta u/\Delta q \sim 0.5$ to 0.8) over 10-15 years, and thus did not obey the one-dimensional theory of consolidation. Since $\Delta u \sim \text{constant}$, both σ and σ' are constants, hence the phenomenon is mainly of rheological nature, or pure creep. No sand-drains were applied under these two fills.

In three other test fills at Skå-Edeby sand-drains were applied with various spacings, 0.9 m, 1.5 m and 2.2 m. The behaviour of these fills over almost 2 years are described in detail by Hansbo (1960). Fig.4 shows the calculated S-t for a drain spacing of 0.9 m. It is interesting to note that the fills with sanddrains activate the settlement potential immediately as a constant value of 0.28 m over the first year. This is almost equal to the long-term creep potential (0.3 m) with no sanddrains, for $t > 6$ years.

TWO AIRFIELD EMBANKMENTS ON SOFT GROUND

The settlement observations for two airfield embankments are shown in Fig.5. The Fornebu embankment in Oslo was started in 1959 and settlement records are available for 5 years or so, Bjerrum (1964). The pilot work area at Kansai International Airport was started around 1988 and settlement records are available until 1991, Geo-Coast '91, Vol.1.

In both cases sand-drains were installed, and a theoretical zero reference time is constructed corresponding to full load application. The calculated settlement potentials are plotted versus time in the lower diagram in Fig.5.

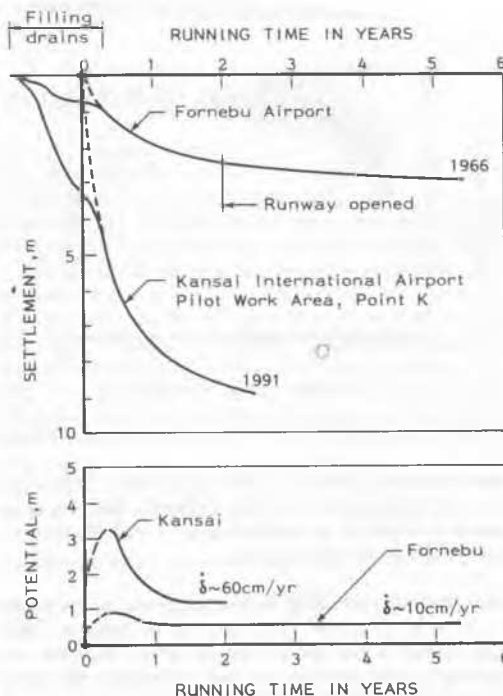


Fig.5. Settlement potentials for two airfield embankments on soft soil, with sanddrains

In both cases a short-term maximum S occurs early, like in Gullfaks C and Skå-Edeby, and then S drops to a lower value. At Fomebu S_c stabilizes at 0.6 m, and since the clay layer was 18 m thick the average field value for the creep number is $r_c = 30$, which is very low because of organic content and large water contents, particularly in the top 10 m.

For the Kansai pilot work area the constant creep potential $S_c = 1.2$ m. The depth of influence H is not known. However, assuming a representative $H = 30$ to 40 m at 9 m settlement (Janbu, 1991) one finds $r_c = 25$ to 33.

TWO SUBSIDENCE RECORDS

Fig.6 contains the registered subsidence versus time for the famous Wilmington Oil Field in California, according to Allen et al (1970). The figure also include the subsidence of the Ekofisk oil field in the North Sea. The shaded area is based on available public data, while the open dashed band of variation is SINTEF's prediction in several reports in 1985-89 for the future development. Zero reference time is constructed for both, since reservoir pressure depletion takes time, like building an embankment.

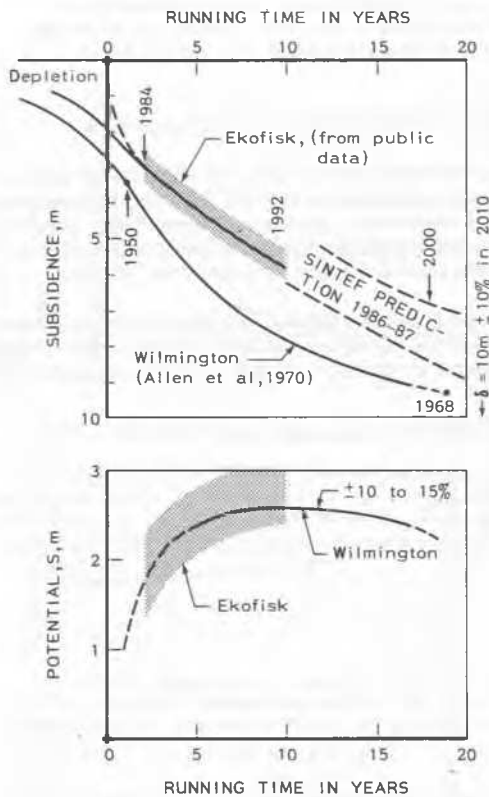


Fig.6. Subsidence potentials for two oilfields, Ekofisk and Wilmington

The calculated settlement potential for Wilmington reach a fairly constant value of 2.5 m, which lasted 10 - 12 years before the field was closed in 1968. Assuming $H = 1000$ m as being effected $r_c = 400$. Probably H was less and thus r_c could be smaller than 400.

The calculated potential for Ekofisk is more uncertain, but the shaded area indicate $S_c = 2.5$ m to 3.5 m now, but it may still be increasing, which is discomfoting, because it may indicate that the vertical thickness of the sediments involved is still growing, and thus will maintain the rate of subsidence at 0.3 m to 0.4 m/year as it is now. Indications are that the field will be closed down or substantially upgraded again before year 2000. Assuming $H = 600$ m to be effected $r_c = 150$ -250, roughly.

CREEP RATES IN THE FIELD

The case records discussed above show that the in situ settlement potentials may remain fairly constant over decades. Moreover, it is often constant far into the primary phase, implying that creep dominates earlier than the classical theories indicate.

If $S_c = \text{constant}$ for $t > t_0$ it follows that the rate of settlement is

$$\dot{\delta} = \frac{S_c}{t} \quad (5)$$

and the additional creep settlement from t_0 until t becomes

$$\delta_c = S_c \ln \frac{t}{t_0} \quad (6)$$

For instance, if $S_c = 3.5$ m and it remains constant at Ekofisk for the next 20 years, the settlement increase will be, roughly

$$\delta_c = 3.5 \text{ m} \cdot \ln 3 = 3.7 \text{ m}$$

This indicates a total settlement of around 9 m in year 2012, and a rate of 0.12 m/year at that time. A rate slowdown is not yet registered so the total settlement could become still larger.

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