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Observational method to predict future settlements

Méthode d'observation pour prévoir de futurs tassements

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ABSTRACT
Settlement observations can well be used to directly predict future settlements. The settlement potential method offers a simple concept for this. Case record evaluations show, that the value of settlement potential reaches a constant value generally after some years, and remains this value for a long period of time. Two approaches are discussed which enable reliable settlement predictions even before a constant settlement potential value is reached. As the settlement potential is based on the time resistance concept, it also provides field values for the creep number. Also other methods are discussed, but they generally need a much longer time period to be able to provide reliable settlement estimations.

RÉSUMÉ
On peut utiliser l'observation des tassements pour prévoir directement de futurs tassements. La méthode du potentiel du tassement est une méthode facile à utiliser à cette fin. L'évaluation des antécédents montre que la valeur du potentiel du tassement atteint une valeur constante généralement après quelques années et reste constante pendant une longue période. Deux méthodes sont discutées. Ces méthodes rendent possible une prédiction fiable du tassement même avant que une valeur constante du potentiel du tassement est atteindu. Puisque le potentiel du tassement est basé sur le concept de la résistance du temps, il fournit aussi des valeurs en place pour le numéro de fluage. D'autres méthodes sont également discutées, mais ces méthodes ont besoin généralement d' une période de temps beaucoup plus longue pour pouvoir fournir évaluations fiables du tassement.

1 INTRODUCTION

Settlement calculation is by no means a trivial task. It is not that seldom that settlement observations, if done, expose inadequacies in the performed calculations. The engineer should then know how to predict the future time – settlement behavior. One possibility is to do a new settlement calculation with revised parameters. However, usually there are no new test results available and the procedure easily turns into curve fitting without any rational basis. Settlement observations offer an other possibility to estimate further settlements. Several different methods are available, but they may produce a large variation in the settlement predictions. Herein the settlement potential method by Janbu (1991) is presented and further discussed. For comparison, also methods by Asaoka (1978) and Korhonen (1977) are used in the analysis of two case histories.

2 SETTLEMENT POTENTIAL THEORY

2.1 *Settlement potential theory*

The settlement potential is defined as the product of the settlement rate and time, i.e;

$$S = \frac{d\delta}{dt} \cdot t \qquad (1)$$

where S is the settlement potential, δ the settlement and t the time. Many case records (Janbu 1991, Janbu 1994, Länsivaara 2003), have shown, that after some time the settlement potential often obtains a constant value, which it keeps for a long period of time. The theoretical significance of equation (1) can be exploited after first recognizing the time resistance concept for creep behavior. Accordingly, the resistance R against time induced compressions i.e. creep, is defined as;

$$R = \frac{dt}{d\varepsilon} \qquad (2)$$

In most soils the time resistance will after some time increase linearly with time. The time resistance can then often be modeled with the simple equation;

$$R = r_s \cdot t \qquad (3)$$

where r_s is the creep number. The creep number relates to the secondary compression index C_α by equation;

$$r_s = \frac{1+e_0}{C_\alpha} \ln 10 \qquad (4)$$

Considering now the settlement potential of a soil layer, and rewriting equation (1) with the aid of equations (2) and (3) one obtains;

$$S = \frac{d\varepsilon}{dt} \cdot H \cdot t = \frac{H}{r_s} \qquad (5)$$

where H is the thickness of the layer. Equation (5) gives then also a theoretical justification of a constant settlement potential. Two important facts should be noted. The creep formulation (3) is generally valid in oedometer testing long before ideal creep conditions, during a linked consolidation and creep phase. Also a constant settlement potential can be found from case records long before all excess pore pressure has dissipated. Consequently this suggests that the consolidation process is after some time actually governed by intergranular shear stress and hence by creep.

Equation (5) makes it also possible to interpret creep parameters from time-settlement records. The field values reflect the true deformation pattern in the soil. This is rarely one-dimensional, especially if the factor of safety is low. It should thus be expected, that the field values indicate more creep deformations than laboratory values determined from oedometer tests.

Although the settlement potential will reach a constant value during the consolidation time, it might still take several years. Before that, some approximation for the settlement potential can be used. Herein two approaches will be discussed

2.2 *Parabolic settlement potential*

According to the classical consolidation theory the primary settlement develops linearly when the settlement is plotted against the square root of time. Applying an approximate solution for the consolidation up to the time t_{50}, one may write;

$$S = \alpha \frac{q}{M}\sqrt{c_v \cdot t} = \frac{1}{2}\delta_p(t) = \frac{1}{4}\delta_p\sqrt{\frac{t}{t_{50}}} \quad (6)$$

where α is a constant, q is load, M is the oedometer modulus and c_v the coefficient of consolidation. According to equation (6) the settlement potential is parabolic in its early phase. Assuming then, that the ideally primary phase and the combined primary and creep phase can be linked at t_{50}, one finds that the constant settlement potential value is one forth of the primary settlement, and that the settlement potential can be written as;

$$S = \begin{cases} S_0 \cdot \sqrt{\dfrac{t}{t_{50}}} & t \le t_{50} \\ S_0 & t > t_{50} \end{cases} \quad (7)$$

Settlement estimations may be obtained by integrating over time the settlement potential in equation (7) divided by time, as seen from equation (1). If the settlement observations have been made in frequent intervals in the start, it is suggested to account for the initial settlement separately.

As the parabolic approximation is based on classical consolidation theory, it may also be used to interpret field values of the coefficient of consolidation.

2.3 *Hyperbolic settlement potential*

Although the parabolic approximation has it bases in classical consolidation theory it has some disadvantages. To be able to use it in the early phase one needs an accurate estimation of the time t_{50}. It can be estimated using the coefficient of consolidation. However, the laboratory values of c_v are generally much higher than the field values (Janbu 1994, Länsivaara 2001). This might be e.g. due to horizontal consolidation. To overcome this shortcoming in the early phase a hyperbolic approximation was introduced (Länsivaara 2001). In the hyperbolic approximation, the settlement potential is described by the equation;

$$S = \frac{t}{a + b \cdot t} \quad (8)$$

In which a and b are parameters of the hyperbola. The physical meaning of these parameters can be obtained by firstly taking the limit value of the equation as time goes to infinity. One will then discover that the inverse of b is the final (constant) value of the settlement potential. Then by taking the time derivative of equation (8) at time zero, one finds that the inverse of parameter a is the initial settlement rate. The settlement potential can thus be written as;

$$S = \frac{t}{\dfrac{1}{\dot{\delta}_i} + \dfrac{t}{S_{p0}}} \quad (9)$$

The justification of using this empirical equation is that its parameters are well defined and can be determined already from early settlement observations.

3 OTHER METHODS

3.1 *Asaoka method*

Only a short review of the Asaoka method will here be given. For further reference, see Asaoka (1978). According to this approach, the primary settlement at a constant time interval can be approximated by;

$$\delta_n = \beta_0 + \beta_1 \cdot \delta_{n-1} \quad (10)$$

where δ_n is settlement at time t_n; δ_{n-1} is settlement at time t_{n-1}; β_0 and β_1 are parameters of the method.

3.2 *Korhonen method*

In the method by Korhonen (1977), the settlements are approximated by the hyperbolic equation (11).

$$\delta = \frac{t}{a_2 + b_2 \cdot t} \quad (11)$$

This is the same equation, which is used in (8) to describe the settlement potential. The inverse of parameter a_2 is the initial settlement rate and the inverse of parameter b_2 the maximum settlement.

4 CASE RECORD EVALUATIONS

4.1 *Introduction*

A comparison of the different approaches to estimate coming settlements from observations was made in 2001 (Länsivaara 2001). In this comparison 60 settlement observation points from 11 sites were analyzed. Herein two of the sites will be discussed in the light of new observations. In addition, the application of the settlement potential to the well known Lilla-Mellösa test embankment in Sweden will be discussed.

4.2 *Murro test embankment*

4.2.1 *General*

Murro test embankment was set up in 1993 in the connection of a road project. It consists of a 2 m high embankment with the dimensions 30 m times 10 m at crest. The subsoil consists of a 1.5 m thick dry crust layer, followed by some 21 m of clayey silt and silty clay with a water content between 46 to 83%.

4.2.2 *Settlement predictions*

When the embankment was built an initial settlement of 90 mm took place. After that the embankment settled with an initial rate of 1.2 mm/day. An estimate for the final settlement potential value can be done with equation (5). Based on an average water content the creep number was estimated to be in the range of r_s = 80 to 120, which results in a settlement potential of S = 175 to 262 mm. Considering also the oedometer tests an initial estimate of the settlement potential of S = 200 to 210 mm was finally made. In a previous study (Länsivaara 2001) settlement predictions were made in chronological order for observation times of ½, 1, 2 and 4 years. The settlement predictions were done by inserting the initial settlement rate into equation (9) and varying the settlement potential to give a best possible fit. Since then, new settlement observations have been taken. In figure 1 observations after one year and the corresponding prediction are presented together with the present settlement observations. The settlement potential value has reached a constant value after a settlement time of three to four years.

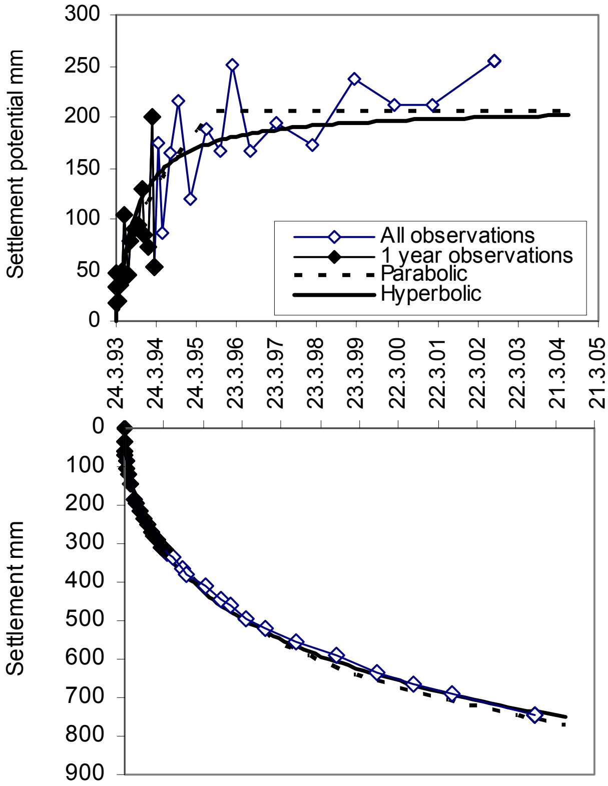

Figure 1. Settlement potential and observed settlements at Murro test embankment. Settlement predictions with the parabolic and hyperbolic approximations of the settlement potential were made based on one year observation time.

As can be seen from figure 1, the prediction after a one year settlement time gave a very good time-settlement prediction trough the whole observation time. This did not occur for the Asaoka and Korhonen methods. In figure 2 the estimations by these methods are presented. Although they both gave very good visual fit in their respective parameter determination and initial prediction curves (Länsivaara 2003), they largely failed in predicting the upcoming settlements.

For the 10.4 year observation time the settlement potential method applying the parabolic approximation gave a settlement of 756 mm, settlement potential method with the hyperbolic approximation 737 mm, Asaoka method 357 mm and Korhonen method 413 mm, while the observed settlement was 747 mm.

The settlement potential value used in the one year estimations were 205 mm for the parabolic approximation and 210 mm for the hyperbolic approximation. In this case they were the same as estimated based on laboratory data.

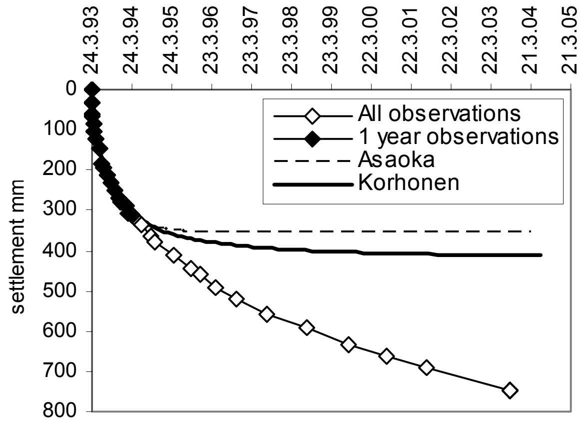

Figure 2. Settlement predictions at Murro test embankment with the Asaoka and Korhonen methods after a one year observation time in comparison to the actual settlement behavior.

4.3 *Light building on stabilized clay*

4.3.1 *General*

This case record provides and example of utilizing observational methods for settlement prediction in practical engineering. A building for a kindergarten was built on soft clay, with a water content between 120 and 50 %. To reduce settlements, the clay below the foundations was stabilized with the deep mixing method. However, at that time the stabilization technology used was still under development. The stabilization did not stop the long time settlements, much due to too low binder amount. After five years, the average settlement of the building was 50 mm and it continued to settle with a rate of 9 mm per year.

4.3.2 *Settlement predictions*

Herein settlement predictions made from observations after five years time (Länsivaara 2001) will be discussed and compared to new observations. Predictions by the settlement potential method, Asaoka method and Korhonen method are shown in figure 3 together with the latest observations.

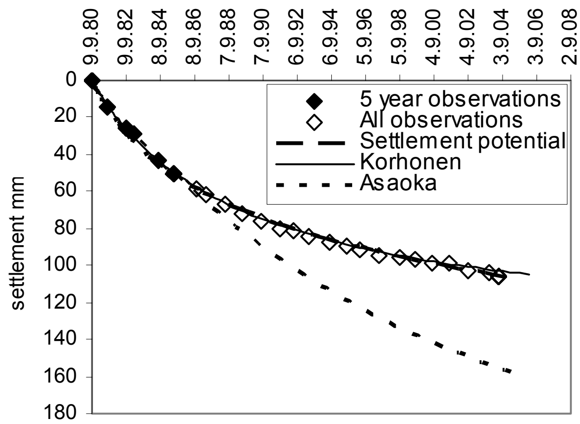

Figure 3. Settlement predictions after a five year observation time compared to all present observations for the kindergarten.

In this case both the settlement potential method and Korhonen method gave very good predictions after a observation time of five years. Asaoka method on the other hand, overestimates present settlements quite largely. For the settlement potential method a constant settlement potential of 35 mm was found after a observation time of 4 to 5 years. The soft layers are approximately 6 m thick, which according to equation (5) results in a creep number of r_s = 170. This is a larger value that could be expected for the soft clay indicating that the stabilization has strengthened the soil, even though it has not been fully successful.

In general a conclusion from several case studies (Länsivaara 2001) was that the settlement potential method provided good settlement estimations from shorter observation time than the other methods. The method by Korhonen also gave relatively good predictions, but for that it required observations from a much longer time period.

4.4 *Lilla-Mellösa test field*

4.4.1 *General*

Two test fills were constructed at Lilla-Mellösa in connection in the search for a suitable site for a new airport for Stockholm in Sweden. The fills have base dimensions of 30m × 30m and a height of 2.5m corresponding to a initial load of 40.6 kPa. For one of the fills vertical drains were installed, while the other was left undrained. Herein only this undrained fill will be discussed.

The subsoil consists of a soft normally consolidated post-glacial clay overlying a varved glacial clay, accounting totally 13.4 m of soft clay layers. The natural water content decreases form about 130 % beneath the crust to about 70 % in the bottom.

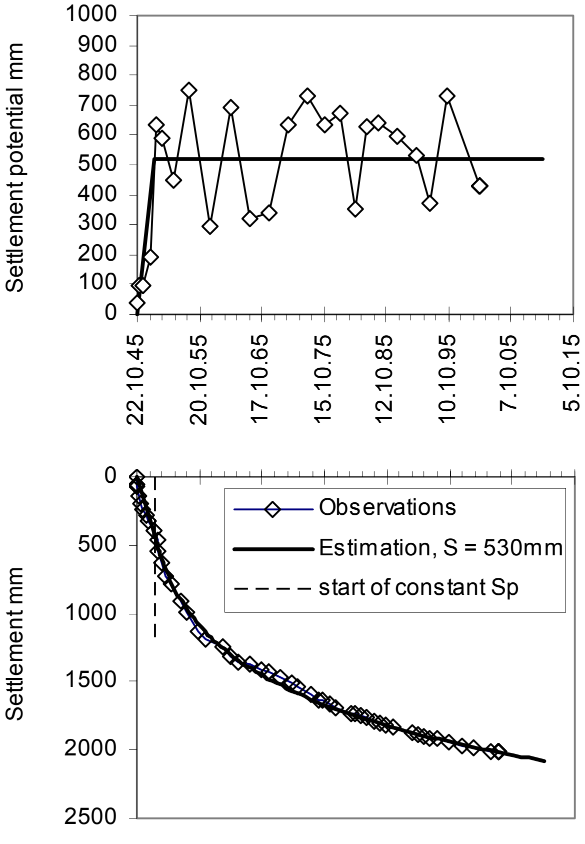

Figure 4. Settlement potential and observations from the Lilla-Mellösa test embankment. The estimation is done by applying a constant settlement potential value after a observation time of 3 years.

4.4.2 *Settlement observations*

The unique thing about Lilla-Mellösa test field is that there are continuous settlement observations from more than 50 years. It is also well instrumented and has been the subject for many studies in Sweden and internationally. It offers thus unique possibilities to test the settlement potential hypothesis validity under a long observation time. In figure 4 the observed average settlements and corresponding settlement potential is presented. As can be seen an approximately constant settlement potential value is reached after three years, and continues during the whole observation time for more than 50 years. The estimation in the lower figure is simply done using the average settlement potential value of 530 mm after the first three years. The settlement rate at a certain time can according to equation (1) be obtained by simply dividing the settlement potential value by the time in question. The present settlement rate is thus 530 mm divided by 59 years, i.e. 9mm/year, which correlates well with the observations (Larsson 2004).

A settlement potential value of 530 mm and a thickness of 13.4 m for the soft layers yield a in situ creep number of $r_s = 25$. This is an extremely low value indicating an exceptional creep willingness. On the other hand the initially 2.5 m high embankment has now settled for more than 2 m. The large settlements and high settlement potential value is partly explained by the low safety of the embankment. The undrained shear strength under the embankment had originally a minimum of 8 kPa.

5 SUMMARY AND CONCLUSIONS

Settlement observations provide valuable information about upcoming settlements and can well be used for predictions. The settlement potential method by Janbu (1991) has proven to give reliable settlement estimates. A constant settlement potential value is often found after a consolidation time of some years, long before end of primary. This indicates that the time settlement process is actually much governed by creep deformations also under the consolidation phase.

Before a constant settlement potential is reached one may use two alternative approximations of the potential value. Especially the hyperbolic approximation enables reliable settlement predictions from relatively short observation times.

As the settlement potential method has it basis in the time resistance concept, it can be used for interpreting creep parameters. It should be remembered, that in situ creep numbers may be much lower than laboratory values, due to non one-dimensional deformations.

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