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A simple method to predict settlement from previous measurements

Une méthode simple pour prédire tassement d'après mesurages antérieurs

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ABSTRACT

A very simple and rather accurate method to predict long-term settlement from previous measurements is presented. It is based on the power function y = a·x^b which suits very well to the settlement observations. The usage of the method is extremely easy compared with other availale methods. The results are compared with the Janbu, Asaoka and hyperbola methods using settlement observations from test embankments and other structures constructed in Finland.

RÉSUMÉ

On présente une méthode très simple et assez exacte pour prédire un tassement à long terme d`après mesurages antérieurs. Cette méthode est basée sur "la fonction de forces" y = a x$^b$, qui est très appropriée à l `observations des tassements. L` usage de cette méthode est extrêmement facile si l`on compare aux autres méthodes. Les résultats sont comparés avec les méthodes Janbu, Asaoka et hyperbola en utilisant les observations de tassement des remblais et autres structures construis en Finlande.

1 INTRODUCTION

It is well known that the prediction of settlements by means of advance calculations includes many error sources and it can lead to highly erroneous results, e.g. http://www.hut...(2004). Sometimes it is of great significance to be able to predict settlements of structures more accurately for tens of years. This is possible by measuring settlements in the course of time from the beginning of the load application and by using these values for the prediction. Several prediction methods have been developed, e.g. the methods by Asaoka (1978) and Janbu (1991). In addition, a method in which a hyperbola is fitted to the observed data has been used (Korhonen, 1977).

Länsivaara (2001) has compared the methods presented above by applying them to 7 structures and embankments with settlement data from periods exceeding 50 years. He has also extended the Janbu settlement potential method by modelling the settlement potential with a hyperbola in a same way as Korhonen applied it to the settlement. In this comparison the Janbu settlement potential method proved to be a superior method to the others.

2 SETTLEMENT PREDICTION METHODS

In Asaoka's method (1978) to predict settlement on the observational basis settlement is estimated in a stepwise manner, Eq. (1).

$$s_n = \beta_0 + \beta_1 \cdot s_{n-1} \tag{1}$$

where s is settlement, n time step and β_0 , β_1 parameters. Observations in $s_n - s_{n-1}$ coordinates form a straight line and parameters β_0 and β_1 are the parameters of this line.

Janbu (1991, 1994) has developed a method called the settlement potential method. The settlement potential R is defined by Eq. (2).

$$R = \dot{s} \cdot t = \frac{\Delta s}{\Delta t} t \tag{2}$$

According to Janbu, the settlement potential usually reaches a constant value after a certain time, and after that long-term settlement predictions can be made. Based on an approximate solution of the consolidation equation the settlement potential can be expressed as Eq. (3).

$$R = \begin{cases} R_0 \sqrt{\dfrac{t}{t_{50}}} & t \le t_{50} \\ R_0 & t > t_{50} \end{cases} \tag{3}$$

where R_0 is the constant value of the settlement potential. The long-term settlement or creep is given by Eq. (4).

$$s = \begin{cases} s_0 + \dfrac{2 \cdot R_0}{\sqrt{t_{50}}} (\sqrt{t} - \sqrt{t_0}); & t \le t_{50} \\ s_0 + 2 \cdot R_0 \left(1 - \dfrac{\sqrt{t_0}}{\sqrt{t_{50}}}\right) + R_0 \ln\left(\dfrac{t}{t_{50}}\right); t > t_{50} \end{cases} \tag{4}$$

where t_0 is the time for the initial settlement s_0.

Korhonen (1977) modelled settlement with a hyperbola, Eq. (5). The same equation was used before e.g. for modelling stress-strain properties (Kondner, 1963).

$$s = \frac{t}{a + b \cdot t} \tag{5}$$

The parameters a and b can be determined graphically if there are enough measurements available. In his study Länsivaara substituted a hyperbola, Eq. (5), for Janbu's Eq. (3), which means that R_0 is obtained from Eq. (6) (Länsivaara, 2001)

$$R_0 = \lim_{t \to \infty} \frac{t}{a + b \cdot t} = \frac{1}{b} \tag{6}$$

3 THE POWER FUNCTION METHOD (PF)

Taylor (1948) developed his well-known square root of time fitting method to evaluate the coefficient of consolidation from oedometer compression readings based on his finding that the theoretical curve on the square root plot is a straight line up to about 60 % primary consolidation, Eq. (7).

$$s = a\sqrt{t} \tag{7}$$

where s is compression from the corrected zero point, t is time and a is a slope coefficient.

Experience has shown that primary consolidation of most normally consolidated clays can be satisfactorily approximated by Eq. (7). A better approximation is obtained by replacing the exponent 0.5 with a variable b, Eq. (8).

$$s = a \cdot t^{b} \tag{8}$$

The curve fitting with a function presented by Eq. (8) is included in many computer programs available for anybody, e.g. the programs Microsoft Excel and Mathcad. If we apply this to oedometer data below 60-70 % primary consolidation, we get very good correlations. The exponent is normally about 0.4-0.6 and the correlation factor is close to 1. As an example, a time-settlement curve of an Otaniemi clay sample at the loading step of 25-50 kPa is presented in Fig. 1a. Nine first observations, from 6 s to 0.5 h (up to 70 % degree of consolidation) represent mainly the primary consolidation. For these values we get a power function $0.6683t^{0.5334}$ with a very good correlation factor $R^2 = 0.9992$. After these nine measurements creep has an increasing effect on the compression, which means that the correlation also becomes worse.

A minimum number of observations needed for the model function, Eq. (8), is three. Fig. 1b shows the variation of the exponent b with time as calculated for each record and two previous records in the time scale. During the primary consolidation stage the value of the exponent b is close to 0.5 and at the end of the primary stage it decreases considerably indicating that the secondary phase is starting.

Fig. 1c presents predictions for the consolidation settlement after 0.5 h. The measured value was 0.447 mm. Predictions were calculated using the model, Eq. (8), for each observation together with 2 and 4 previous observations (together 3 and 5 settlement records) and for each observation together with all the previous observations (denoted as "all"). The figure shows that relatively good predictions were obtained at a very early stage of consolidation.

After curve fittings to numerous test data, it was found that three last observations had many advantages compared with five or more observations, for example:

- less data to be handled
- if the fitting is poor in a wide range of observations, the result is more inaccurate the more observations are included
- creep can also be predicted after the primary consolidation

4 COMPARISON WITH FIELD MEASUREMENTS

The model presented by Eq. (8) can equally be applied to the field measurements. Creep cannot be predicted with primary consolidation data but the prediction shall be restricted to the consolidation settlement. Creep can, however, be modelled in the same way as the primary consolidation using settlement data obtained during secondary consolidation.

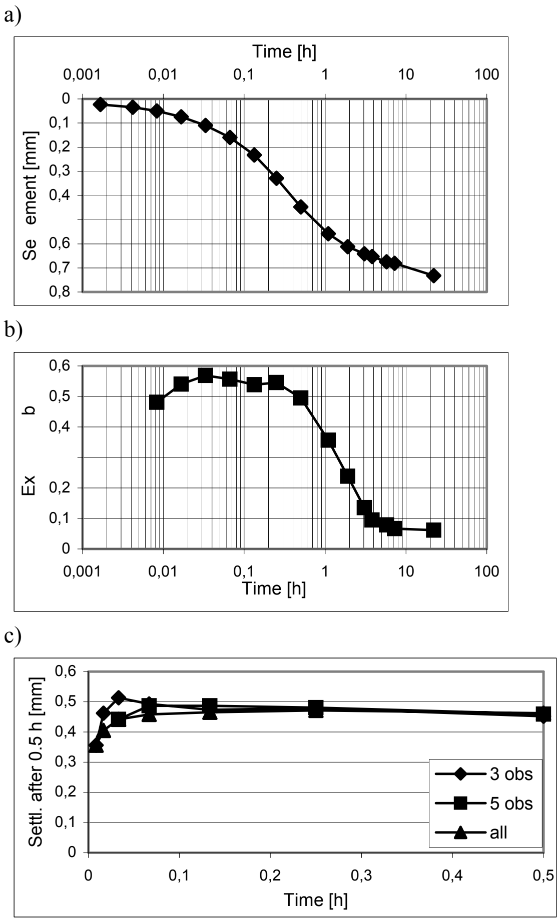


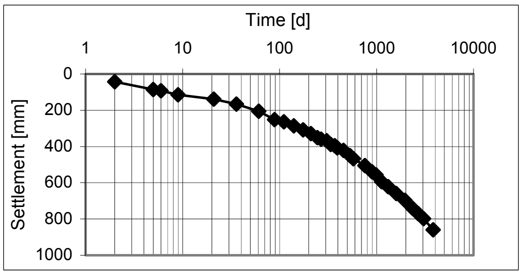
Figure 1. Otaniemi clay. a) An oedometer test result at the loading step of 25-50 kPa. b) Exponent b versus time in the same test. c) Settlement after 0.5 h as predicted at different points of time.

4.1 *Murro test embankment*

Settlements of the Murro test embankment in Finland (e.g. Koskinen & al., 2002) have been measured for more than 10 years, in which time the centre line of the embankment has experienced a settlement of 858 mm. Fig. 2a shows that the primary settlement is still going on after 10 years. Fig. 2b presents the predicted settlements for 10 years at different points of time using 3 and 5 last observations. A lot of scattering is seen at the beginning, but after 1-2 years the error is within 10 %.

Fig. 3 presents the comparison by Länsivaara (2001) of the predictions for 7.4 years in which the predictions of the power function method (PF method) with 3 and 5 observations are included. The observation periods vary between 0.5 and 4 years. The measured settlement of 663 mm is marked with a horizontal line. The figure shows that the predictions of the PF method are clearly better than those of the Asaoka and hyperbola methods and do not differ much from those of the Janbu method.

a)



b)

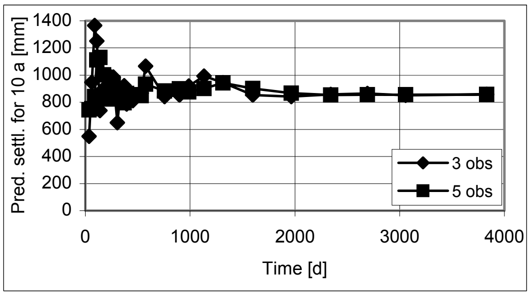


Figure 2. Murro test embankment. a) Measured settlements at the centre line. b) Settlement after 10 years predicted by the PF method at different points of time. Measured settlement 858 mm.

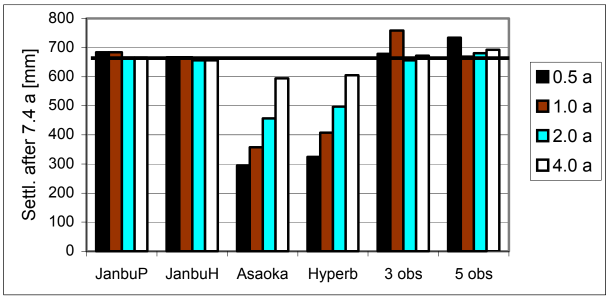


Figure 3. Murro test embankment. Settlements after 7.4 years predicted at different points of time. Measured settlement 663 mm. (JanbuP = parabola fitting, JanbuH = hyperbola fitting)

4.2 *Haarajoki test embankment*

The Haarajoki test embankment was constructed in 1997 and observations encompass more than five years (http://www.hut... , 2004). Figure 4 presents the PF predictions of the settlement at the centre line of the station no. 35880 representing the biggest settlement of the vertical drainage area. After inaccuracies at the beginning, the predictions settle almost at the measured level of 785 mm. In this case the PF fitting of 5 records resulted in a worse prediction than that of 3 records.

Fig. 3 presents the comparison of the predictions for 20 years (Länsivaara, 2001) in which the predictions by the PF method with 3 and 5 observations are included. The observation periods vary between 0.5 and 3.5 years. No major differences exist between the predictions of the Janbu and the PF method, but those of the Asaoka and the hyperbola methods are far from the others. The prediction of the settlement after 5 years obtained with the Janbu and PF method differ considerably from that of the other prediction periods. This is probably due to the disturbance caused by construction and initial settlement.

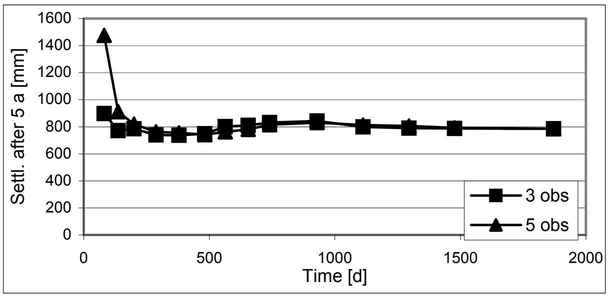


Figure 4. Haarajoki test embankment. Settlement after 5 years predicted by the PF method at different points of time. Measured settlement 785 mm.

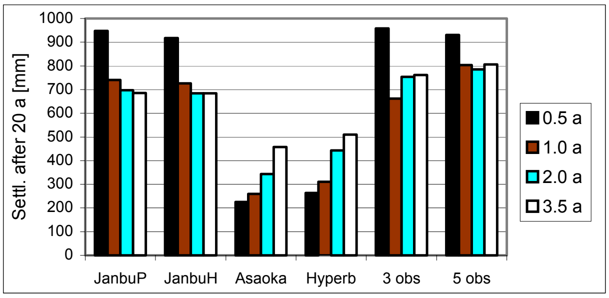


Figure 5. Haarajoki test embankment. Settlements after 20 years predicted at different points of time using different methods.

5 CREEP

The separation/connection of the primary consolidation and creep between the degree of consolidation of U = 50 – 100 % has exercised the minds of researchers for a long time. The settlements of the test embankments presented above are at the primary stage and creep has not yet started (see e.g. Fig. 1, the time period 0 – 0.5 h). In the report by Länsivaara (2001) also the engine shed and the railway turntable of Kerava were included. Their record periods exceed 50 years while the primary consolidation time was about 10 years. In addition to the hyperbola method also the Janbu settlement potential method highly overestimated the 50 years settlement as the predictions were made for observation periods less than 10 years from construction. In general, the researchers apply a different prediction model to the primary consolidation and creep, but work has been done to develop methods to handle them together, e.g. Svanö et al. (1991).

It is obvious that also the PF method overestimates settlement the more the more far to the secondary stage it is applied, but if observations exist also from the creep phase, the prediction becomes more accurate. Because the Kerava records discussed above were not available, an example of the application of the metod to a long-duration oedometer test result at 50 kPa loading is presented in Fig. 6. Settlements for 3 weeks (504 h) were modelled on the basis of 3 previous settlement records.

According to Casagrande's method t_{100} = 10,81 h in the test. Before 24 h the modelled settlements have far too high values, but after that they are accurate. Thus the PF method is able to model also creep provided that 3 observations from the secondary consolidation phase are available.

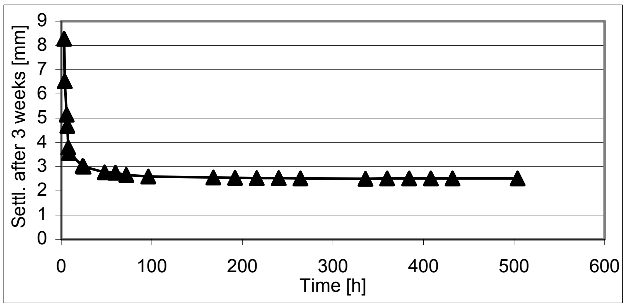


Figure 6. Vanttila clay. Predictions at different points of time for an oedometer test settlement after 3 weeks (504 h) using the PF method. Obseved settlement 2.509 mm.

6 CONCLUSIONS

A method to predict long-term settlement from previous measurements was presented. It can be regarded as an extension of the square root of time fitting method in which the square root is replaced by a power function (PF method). The method was compared with Asaoka's method, Janbu's settlement potential method and the hyperbola method using settlement data obtained from two test embankments constructed in Finland.

As a result of the comparison, the PF method proved to predict the settlements of the two test embankments involved in the comparison clearly better than Asaoka's method and the hyperbola method. No major differences existed between the results of the PF method and Janbu's method, the results of Janbu's method being more consistent. A superior advantage of the PF method was its ease of use.

The PF method is also able to model creep provided that 3 observations from the secondary consolidation phase are available.

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