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Potential application of satellite data in evaluation of field creep calculation

Le potentiel d'utilisation de données satellites dans l'évaluation du calcul de fluage des terrains

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ABSTRACT: Soil parameters interpreted for long-term settlement analysis can easily be affected by sample disturbance or the adopted test procedure. Still, it is normal to encounter situations where one has to make settlement analysis based on available data. In such cases, it is important to evaluate the representativeness of the interpreted creep parameters. In this paper, different ways of evaluating creep parameters are first briefly presented and discussed. In recent years, satellite based remote sensing techniques are shown to monitor ground movements with high precision. A way to supplement evaluation of creep parameters using satellite data is explored in the work presented in this paper. This is further illustrated by using different sets of parameters and along with numerical simulations based on the isotache concept. It is shown that by using such data, there is a huge potential to evaluate and establish the initial creep rate reasonably well and this is illustrated to supplement creep calculations. Additional possible use of satellite data in connection to evaluation of settlement are also discussed.

RÉSUMÉ: Les caractéristiques de compressibilité interprétées pour le calcul de tassement à long terme, peuvent être affectées par le remaniement de l'échantillon ou la procédure d'exécution de l'essai adoptée. Cependant, il est normal de se trouver dans des situations où l'on doit procéder à une analyse de tassement à partir de données disponibles. Dans tels cas, il est important d'évaluer la représentativité des paramètres de fluage interprétés. Dans ce travail, différentes façons d'évaluation des paramètres de fluage sont présentées et discutées. Au cours des dernières années, les techniques de télédétection par satellite sont présentées pour surveiller les mouvements du sol avec une grande précision. Dans ce travail, un moyen pour supplémenter l'évaluation des paramètres de fluage à l'aide de données satellites est exploré. Ceci est illustré plus en détail en utilisant différents assortiments de paramètres et avec des simulations numériques basées sur un concept Isotache. Il est montré que par l'utilisation de telles données, il y a possibilité de raisonnablement bien évaluer et d'établir la vitesse initiale de chargement et cela est illustré pour parfaire les calculs de fluage. L'utilisation potentielle supplémentaire de données satellitaires pour l'analyse de tassement est également discutée.

KEYWORDS: Settlement, creep, secondary consolidation, sample disturbance, sample quality, satellite data.

1 INTRODUCTION

Correct prediction of long-term field settlements requires soil parameters interpreted from representative samples of high quality. However, obtaining high quality samples is challenging as sampling itself inherently affects the soil structure thereby inducing unavoidable sample disturbance. Soil parameters interpreted from disturbed samples give unrealistic initial creep rate, which ultimately lead to overestimation of creep deformations. As a result, one has to always evaluate the implications of the interpreted creep parameters. However, this evaluation is usually based on experience. In this work, an approach to supplement evaluation of initial creep rate using satellite data is presented. In recent years, the remote sensing technique abbreviated as InSAR (Interferometric Synthetic Aperture Radar) is shown to monitor ground movements with high precision. These measurements can also easily cover large areas and provide settlement rates with high sampling frequency. Comparison of deformations measured using satellite with other direct measurement techniques are shown to be promising (e.g. NGU 2003, Cetinic et al. 2015, Löfroth et al 2015; NPRA, 2016). Such satellite data is presented for a site in Oslo Harbour, Bjørvika bay, Norway. This work discusses key parameters that govern creep calculations and their evaluations for use in order to get a reasonable field prediction. In doing so a set of soil parameters are established and numerical analysis is also performed. Implication of different parameter set is discussed in light of implied creep rate, age of the clay layer and satellite data. This work also presents additional potential use of satellite data in assisting evaluation of field settlements.

2 MEASUREMENT OF DEFORMATION USING SATELLITE-BASED RADAR INTERFEROMETRY (INSAR)

Synthetic Aperture Radar (SAR) system is an instrument that is normally installed on Earth-observation satellites that continuously move in near-polar orbits between 500 and 800 km above ground. The SAR instrument is relatively insensitive to light and meteorological conditions making it an extremely valuable tool for the long-term study of dynamic processes on Earth (Cetinic et al. 2015). As the satellite moves along its orbit, it images an area by transmitting series of electromagnetic waves in pulses towards the earth surface which are reflected back to the satellite after impacting the ground. Thus, the measurements are dependent on obtaining reflectors on the ground to detect its relative motion over a certain period. These deformations can result due to various natural phenomena or manmade activities, e.g. landslides, creep deformation, swelling and shrinkage effect of clays, ground dissolution due to active chemistry, underground construction works or mining activities, ground subsidence due to ground water extraction or lowering and tectonic movements, for more details see for example Bateson et al. (2012). Use of InSAR data for detecting and measurement of ground deformation is increasingly becoming popular due to increased precision and the ease of accessing such data. Particularly, the Norwegian Public Roads Administration (NPRA) has recently had a research project with a focus on monitoring of rock slides using satellite date and monitoring settlements on infrastructures adjacent to roads.

A typical processed satellite data is shown in Figure 1 for an area where significant settlement rates have been observed in connection with construction activities. This area is located around Oslo Central station and the Bjørvika bay in Oslo Harbour, Norway. The area has been a subject of extensive settlement study (e.g. Karlsrud et al. 2013, NPRA 2016). A major land reclamation has taken place close to the bay in between approximately 1650 and 1850 leading to 2 to 8 m thick fill placed on previous sea bottom. The soil in the area primarily consist of marine clay extending to bedrock found at depths up to 80 m (Karlsrud et al. 2013). Figure 1 gives average annual settlement velocity with various colours representing points where there are reflectors. It gives satellite data measured from 1992 to 2000. Depending on the size of the areas where the averaging is made, a settlement rate of ca. 3 to 6 mm/yr is observed around the central part of the area shown in Figure 1. An important aspect in using satellite data is to take the postglacial isostatic uplift of the ground into consideration.

Figure 1. A processed satellite image giving average annual displacement rates (velocity) in central part of Oslo, Norway (https://maps.globesar.com/).

3 ON MODELLING ASPECTS OF CREEP

Deformation of saturated soil is usually studied, in the current practice, by dividing it into two consecutive phases referred to as primary and secondary consolidation phases, where the primary phase consists of both effective stress- and time-dependent (creep) deformations and the secondary phase is dominated by creep deformations. Incorporation of creep during primary consolidation has been a topic of discussion since Ladd et al. formally defined creep hypothesis A and B in 1977. Extensive laboratory and field data have clearly showed that it is hypothesis B that convincingly describes creep during primary consolidation as well as the rate dependency of clays in general (e.g. Leroueil 2006, Degago et al. 2011, 2013).

The isotache concept, which implies creep hypothesis B, states that there is a unique relationship between the current strain rate (change in void ratio), effective stress state and strain (void ratio) valid throughout the entire deformation process (Šuklje 1957). Such modelling approach is thus used as a basis in the work presented in this paper as it can conveniently be used for modelling rate dependency of clays. This is demonstrated using an elasto-viscoplastic soil model available in the FE code Plaxis, i.e. the Soft Soil Creep (SSC) model (Stolle 1999). The model is based on the isotache concept (Šuklje 1957, Bjerrum 1967). The SSC model is isotropic and does not take into account the effect of destructuration. However, for the commonly encountered road embankments and fillings, an isotropic formulation is considered sufficient and the effect of destructuration can be studied by assessing effect of various combinations of the input parameters. By keeping anisotropy and destructuration out of the picture, this work focuses on evaluations of the creep parameters, based on the isotache formulation as adopted in the SSC model.

3.1 *Key parameters governing creep calculations*

The isotache concept uniquely relates equivalent effective stress state (p^{eq}), equivalent reference pre-consolidation stress (p_0^{eq}) and volumetric creep strain rate ($\dot{\varepsilon}_v^{vp}$). This relationship, as used in the SSC model, is presented in Eq. 1.

$$\dot{\varepsilon}_v^{vp} = \frac{\mu^*}{\tau} \cdot \left(\frac{p^{eq}}{p_0^{eq}} \right)^{\frac{\lambda^* - \kappa^*}{\mu^*}} \qquad (1)$$

where λ^* and κ^* are the modified compression indexes for virgin compression and recompression line respectively; τ is a reference time corresponding to the specified over consolidation ratio (*OCR)* or (p_0^{eq}/p^{eq}). Typical value of τ is usually selected to be one day as standard incremental oedometer tests are ran with one-day increments. As can be seen from Equation 1, in addition to μ^*, the ratio $(\lambda^* - \kappa^*)/\mu^*$ and *OCR* are very important for the calculated creep strain rate.

In Scandinavia, one typically finds clays in normally consolidated state, with only an apparent OCR resulting due to aging (Bjerrum, 1967). For such cases, Eq. 2 can be used to estimate either the age of a clay (t_{age}) implied when an OCR corresponding to a certain τ is known; or, to estimate an OCR corresponding to a certain reference time τ when t_{age} is known. This implies that one must assume that the ratio $(\lambda^* - \kappa^*)/\mu^*$ is constant in time (with deformation). However, in general this does not imply that λ^* or μ^* are constant with time, even though this is the assumption in the SSC model.

$$t_{age} = \tau \cdot OCR^{\frac{\lambda^* - \kappa^*}{\mu^*}} \qquad (2)$$

4 ON SAMPLE DISTURBANCE AND PARAMETER INTERPRETATION

Numerical calculations of field conditions are normally based on soil parameters interpreted from laboratory tests. Hence, it is crucial that the laboratory samples have the desired level of quality and be representative of the soil in-situ to give acceptable prediction of field performances. Correct interpretation of OCR crucially hinges on the sample quality as it can easily be affected by sample disturbance (Different quality of samples will also give different stress and time compressibility parameters (e.g. Leroueil & Kabbaj 1987, Long et al. 2009, Berre 2014, Degago and Grimstad 2014).

To numerically illustrate role of sample quality, one could ideally interpret soil parameters from varying quality and study their implications as done by Degago and Grimstad (2014) for a well-documented test fill in Sweden. For the work presented in this paper, it was, however, not possible to compare data from high and low quality samples to illustrate the role of sample quality. On the other hand, it is not often that one enjoys the benefit of such information for commonly encountered geotechnical problems. For Bjørvika area, the available sample data for settlement analysis is not of highest quality one can obtain and the implications of the parameters interpreted from such samples thus has to be assessed. This is therefore an interesting example to illustrate the commonly encountered scenario of having to design or analyse settlement with available soil data. Details of ground investigations carried out in the Bjørvika area are reported in various references (see summary in NPRA 2016). These references have made the basis for this study. Several samples are taken and analysed from the

Bjørvika area. Samples, which have relatively best quality, are used to establish creep parameters and these are given as a first set in Table 1. Set 2 is used to show the effect of OCR = 1.0. Set 3 and 4 represent another possible parameter set based partly on interpretation of partly on an assumption of $\mu^*/\ \lambda^*=0.045$ and $\kappa^*/\ \lambda^*=0.1$. Set 5 is a variation of set 1 where a higher OCR value is selected from age considerations. The various sets are meant to illustrate the various possible scenarios for assessing and evaluating of creep parameters.

Table 1. Different soil parameter sets for the clay layer in Bjørvika area.

Parameter, Symbol [unit]	Parameter sets				
	Set 1	Set 2	Set 3	Set 4	Set 5
κ^* [-]	0.009	0.009	0.0066	0.0167	0.009
λ^* [-]	0.073	0.073	0.0660	0.1667	0.073
μ^* [-]	0.003	0.003	0.0030	0.0075	0.003
OCR [-]	1.4	1.0	1.3	1.3	1.75
$(\lambda^* - \kappa^*)/\mu^*$[-]	19.8	19.18	20.04	20.00	21.33
$\dot{\varepsilon}$ [%yr^{-1}]	0.19	121.8	0.57	1.44	0.0007
t_{age} [yr]	1.74	0.003	0.53	0.52	419.3

5 EVALUATING INTERPRETED PARAMETERS

Even though one ideally aims to acquire a sample with highest quality possible, it is still common to encounter situations where field settlement analysis has to be based on available samples that could be of low quality. An important challenge is that one does not normally have the benefit of comparing this with a sample of high quality to reveal the extent of sample disturbance. It is thus important to study the implications of interpreted parameters and evaluate them. Sample disturbance can affect key parameters of creep and this is exemplified by interpreting creep parameters for the tests presented in Table 1.

Degago and Grimstad (2014) illustrated, in detail, evaluation of parameters by calculating the initial creep rate (using Eq. 1), the implied age of the clay (Eq. 2) and assessing the ratio $(\lambda^* - \kappa^*)/\mu^*$ (which shall be in the range of 15 – 50). These are also computed for different sets given in Table 1. For the parameter sets given in the table, the ratio $(\lambda^* - \kappa^*)/\mu^*$ is within the expected range and more or less similar with less distinction among all parameter sets. The initial creep strain rate and implied age is seen to be different. Set 2 gave unrealistically high initial creep rate as compared to the others. For set 1, set 3 and set 4 the initial creep rate is relatively low (as compared to set 2). However, evaluation of these combinations becomes clearer when one looks at the implied age which is shown to be too short for such clay layer that has experienced apparent over-consolidation due to creep. Set 5 gives the lowest initial creep rate and an implied age in the order of what one can expect for such clays. Thus this set shall be closer to the reality looking at evaluation of the interpreted parameters.

It is worthwhile to note that the interpreted OCR from the oedometer test may not be the same as the one that should be used in a model. One reason for this, in addition to sample disturbance, is that oedometer tests have an inherent limitation as the test is not ran from the true initial state of stress in-situ (Degago and Grimstad, 2014).

6 EVALUATIONS BASED ON TERRAIN CREEP RATES

Calculating settlement due to an increase in effective stress over a certain period of time, gives settlement contribution due to time effects (creep). Therefore, one has to evaluate the total settlement by decomposing it into settlement due to effective stress and due to time increase. This can be done by modelling the problem with correct stress conditions and examining the virgin (natural) terrain settlement or far field settlement implied by the parameters. Hence, this gives another important way of evaluating representativeness of creep parameters. Such approach is exemplified using an FE-simulation of a simplified geometry from Bjørvika.

A sand layer of 2 m overlaying 30 m of clay layer is modelled using a very fine mesh in Plaxis. The ground water table (GWT) is located at the terrain level and drainage is allowed at the top and bottom. A constant permeability of 0.02 m/year is used for the clay layer. The simulation is run for 100 years using various parameter sets as given in Table 1. The time steps are controlled manually to enhance accuracy and uniformity of output settlement data. The resulting virgin terrain settlements and settlement rates of the clay layer are respectively given in Figure 2 and Figure 3.

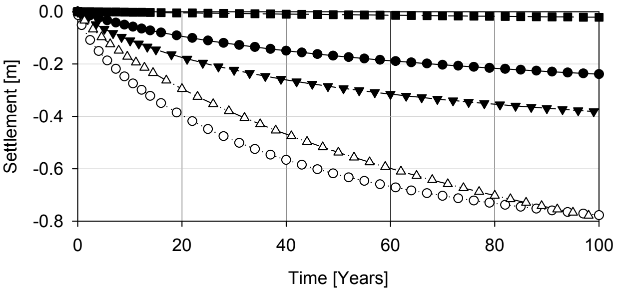

Figure 2. Virgin terrain settlement vs. time calculated for various parameter sets as given in Table 1.

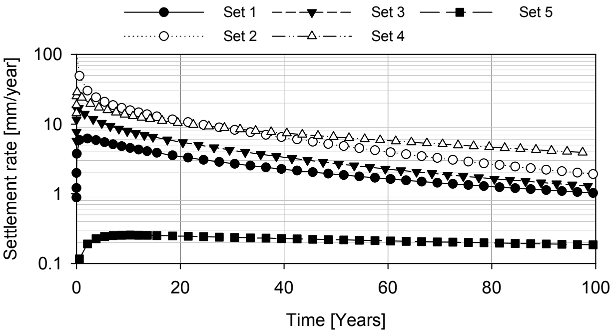

Figure 3. Virgin terrain settlement rates vs time as implied by the parameter sets given in Table 1.

When one calculates settlement due to an increase in effective stress using parameter set 2 and 4, a significant part of the settlement could have come just from the unrealistic virgin terrain settlement, i.e. ca. 0.8 m for the example in this work (Figure 2). Therefore, this is a good example to illustrate that one has to evaluate total settlement by examining the contribution of the terrain settlement as well. This can also be used to compute the virgin terrain settlement rates. Having satellite data in such cases is very attractive to evaluate the correctness of the calculation by comparing it directly with the calculated settlement rates. For the sake of comparing the current deformation rate from satellite, one can define the "current" time for the calculations to be within the time span of around 5 years. This is because numerically it takes a certain time to build up excess pore pressure that gives a desired deformation rate. In the calculated cases, the peak excess pore pressure were attained within 5 years from start of calculation. Thus if one looks at deformation rates around 5 years, Figure 3, it is seen that set 2 gives the highest deformation rate (ca. 20 mm/yr) and generating unrealistically high excess pore pressure (i.e. ca. 40 kPa at the middle of the clay layer). The virgin terrain deformation rates of set 3 (16 mm/yr) and set 4 (10 mm/yr) are considered high the generated excess pore pressure of 17 and 23 kPa respectively. Set 5, based on age considerations, gave the lowest deformation rate (ca. 0.25 mm/yr) with a stable rate over most part of the calculation time span and lowest excess pore pressure generation (ca. 0.5 kPa). The second lowest deformation rate (ca. 6 mm/yr) is observed for parameter set 1 with maximum excess pore pressure of 8 kPa. Comparing with the satellite data of the area, Figure 1, a parameter set with OCR between 1.5 and 1.75 seems to be the most representative. It is important to note that the high settlement rates measured in the area (Figure 1) are significantly influenced by construction activity that lead to reduction of pore pressure. This is thus expected to be higher than settlement rates from time effects only on virgin terrain. Otherwise, away from this area, the natural (virgin) deformation rate is seen to be in the order of ca. 0.5 mm/yr (Karlsrud et al. 2013).

7 ON FURTHER POTENTIAL USE OF SATELLITE DATA IN SETTLEMENT EVALUATION

Use of satellite data in connection to evaluation of field creep calculation is already presented in detail. Apart from this specific aspect, there is a wide application potential in settlement evaluation in general.

Settlement is controlled by the extent of the planned construction activity and the behaviour of the underlying soil. The Norwegian Public Roads Administration (NPRA) guideline (N200) requires that settlements should be within the permissible limits. An important step at a preliminary phase is to first identify sections of road where settlement is expected. Having satellite data can thus be an important start point in evaluating this as it clearly gives the current settlement rates. Roads usually extend over a huge area as compared to buildings and having such satellite data can be used to identify settlement potential areas effectively. During the design stage, such data can also be used to optimise planning of ground investigation scheme. For evaluation of the performance of roads or railways, the gathered data can be used to identify sections with excessive settlement and to plan for maintenance. Satellite data can also be used to monitor if road construction activity has induced settlement of adjacent buildings and infrastructures. This way of monitoring is cost and time effective. NPRA will actively peruse exploring wider potential use of satellite data in connection to road construction.

Detailed future work is necessary to calibrate satellite data with direct measurement and increase the accuracy even more. An activity is already underway to establish new research benchmark test sites in Norway (L'Heureux1 et al. 2017). These test sites shall be fully characterized and as part of this, installing reflectors, on the test sites to enable measurement of satellite data is considered. This can then form a basis to further explore use of satellite data in settlement evaluations.

8 FINAL REMARKS

In design stage of projects where one has to make settlement calculations, one should ideally base this on soil parameters interpreted from high quality samples. However, it is usually not easy to guarantee this as there is always a certain degree of sample disturbance involved due to the inherent nature of sampling itself. Another important challenge is that even though one can tell that there is sample disturbance, it is difficult to exactly assess the extent of the disturbance in relation to undisturbed sample. Therefore, it is important to be able to evaluate the representatives of the interpreted parameters since this forms the basis for the correctness of the calculations. Calculating implied age of the soil and the implied initial creep rates can for example do this. This in turn requires evaluation based on experience or other references such as long-term field measurements and samples of high quality. However, one does not normally enjoy the benefit of having such information. Therefore having a satellite data that can give settlement rate becomes an attractive alternative. The data can be used during preliminary design stage to identify settlement prone areas and during detailed design to calibrate model parameters. After road construction such data can still be used to effectively monitor on going settlements on the road and adjacent infrastructures.

This paper emphasizes using the best estimate values to make predictions and to check virgin terrain settlement rates and calibrate it with measured satellite data. Such satellite data enables to assess if combination of creep parameters is correct or if adjustment of some soil parameters most influenced by sample disturbance is necessary. In this way, one can evaluate and establish the initial creep rate reasonably and this is illustrated to supplement the creep calculation. Future detailed research works on this promising prospect are important.

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