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Undrained creep susceptibility of clays

Compartement fluage non-drainé des argiles

Suzanne Lacasse & Toralv Berre
International Centre for Geohazards, Norwegian Geotechnical Institute, P.O. Box 3930 Ullevaal Stadion, 0806 Oslo, Norway

ABSTRACT
The paper reviews the different components of settlement and essential concepts of undrained creep of saturated clays. The results of triaxial and simple shear undrained creep tests on a Norwegian clay are compared to the results reported in the literature. The undrained characteristics are assembled in a creep susceptibility diagram and analysed as a function of the behaviour of other materials known to be creep susceptible. A procedure to estimate the creep susceptibility of a clay in practice is proposed.

RÉSUMÉ
L'article rappelle les composantes du tassement et les concepts essentiels du fluage non-drainé des argiles saturées. Les résultats d'essais de fluage au triaxial et au cisaillement simple sur une argile norvégienne sont comparés aux résultats de la littérature. Les caractéristiques non-drainées sont portées sur un diagramme de susceptibilité au fluage et analysées en fonction du comportement de matériaux connus pour leur tendance au fluage. Une approche pour estimer la susceptibilité au fluage en pratique est suggérée.

1 INTRODUCTION

Undrained creep is of concern when the safety factor of structures on clays is low. Undrained creep can reduce the shear strength available in clay and can produce shear strains large enough to substantially increase the settlements of a structure.

The paper reviews the components of settlement and presents the results of undrained creep tests on several clays. Constant volume direct simple shear and triaxial creep test results are combined with published results to estimate creep parameters. The undrained creep characteristics are assembled in a creep susceptibility diagram.

A review of past work on undrained creep suggests that there are very few cases of practical proven methods of predicting undrained creep deformations. Cases of excessive creep deformations are found essentially only for very highly plastic clays with a high organic content. For foundations with material coefficient above 2.5 under a static vertical load, the undrained creep deformations due to the vertical load will be very small compared to the consolidation settlement unless the clay is highly creep susceptible. The danger of a creep failure can usually be ruled out unless the safety factor under the static vertical load is below 1.5 (D'Appolonia *et al.*, 1971).

2 COMPONENTS OF SETTLEMENT

2.1 *One-dimensional static loading*

For essentially one-dimensional static loading condition of a saturated clay, the generally accepted settlement model includes:

- s_{cf} = final consolidation settlement from a conventional 1-D analysis, also denoted as s_{oed}
- S_c = primary consolidation settlement = $\bar{U}_v \cdot s_{cf}$ where $\bar{U}_v$ = average degree of consolidation for vertical drainage
- s_{sc} = continued long term settlement due to drained creep and often called secondary compression.

This model is idealized in that no creep is assumed to occur during primary. This assumption is considered reasonable, at least compared to the accuracy of estimating the magnitude of s_{cf}, although some creep settlement will also occur during primary consolidation.

2.2 *Two- and three-dimensional static loading*

For non one-dimensional conditions, where the rate of load application is small compared to the time required for primary consolidation, the clay foundation will undergo some undrained shear strains, this producing lateral deformations and an "initial" settlement s_i. Under constant load, consolidation proceeds, due to combined vertical and horizontal drainage. The lateral deformations will also continue to increase, this causing an additional settlement, denoted s_{cr}, i.e. "creep settlement" due to shear strains under constant load. It is assumed that s_{cr} is mainly caused by undrained creep and that drained creep of the type considered for 1-D loading is negligible. Other factors that will influence the importance of creep for a clay foundation are the length of the drainage path and the coefficient of consolidation. The most critical situation with respect to undrained creep will therefore be thick deposits of soft clays with low coefficient of consolidation.

Long term settlements due to creep, i.e. the magnitude of s_{cr}, are seldom if ever estimated, at least as part of conventional geotechnical practice. No generally accepted procedure exists for making such predictions. Typical practice would usually estimate the "final settlement" as equal to s_{oed}, although for major projects one might also add a component for the initial settlement and perhaps reduce the final consolidation settlement, s_{cf}, to account for an excess pore pressure being less than the increase in total vertical stress, as proposed by Skempton and Bjerrum (1957).

2.3 *Observations of field performance*

Foott and Ladd (1981) review three case histories (Atchafalaya flood control levees, storage tanks on plastic organic clay in New Jersey, and Cross River embankments constructed on thick organic plastic clay) where the measured field settlements either greatly exceeded the predicted primary consolidation settlement or at least appeared to have values of initial settlement, s_i, and/or creep settlement, s_{cr}, that were large compared to the final consolidation settlement based on a conventional 1-D analysis. Foot and Ladd conclude that some plastic or organic clays have unusually low normalised modulus E_u/s_u (where E_u is Young's secant modulus and s_u is the undrained shear strength), which may lead to excessive initial settlements. Large initial settlements are often followed by excessive undrained creep movements if consolidation occurs very slowly.

Tavenas *et al.* (1979) and Tavenas and Leroueil (1980) summarize over 20 case histories relating measured centerline settlements and lateral deformations which occurred during and after construction of embankments on soft clay deposits. The authors concluded that: (1) during initial construction when the consolidation stress is still less than the preconsolidation stress, rapid partial consolidation occurs; (2) once the preconsolidation stress is reached, the loading becomes essentially undrained and most of the settlement is due to lateral deformations; (3) after the end of loading and during consolidation, the lateral deformations continue to increase and the shape of the normalized displacement versus depth curve remains approximately constant.

3 UNDRAINED CREEP OF SATURATED CLAYS

Because of space limitations, an exhaustive review of previous work is not possible in these proceedings. Only some of the more important aspects are presented. Figure 1a plots strain versus time for three test run with different stress levels D (D = applied stress as a fraction of the undrained stress causing failure at some reference strain rate or rate of loading). Sample 1 exhibits only "primary" creep, as the strain rate decreases with time. Sample 2 first undergoes primary creep, and then exhibits "secondary" creep, as the strain rate becomes more or less constant Sample 3, at a higher stress level, exhibits "tertiary" creep where strain rate accelerates, eventually ending in a creep rupture. Extensive creep data show that secondary creep should be considered as a transition zone between primary and tertiary creep.

3.1 *Creep rupture*

Creep rupture refers to failure which occurs at the end of the tertiary creep phase where strain rate keeps increasing. Singh and Mitchell (1969) developed a semi-empirical approach for characterisation of the interrelationship among creep (strain) rate, stress level (D) and time (t). Figure 1b shows the basic plots used for presentation of creep data and evaluation of the three parameters used in the rate process equation (strain rate = $Ae^{\alpha D}(t_1/t)^m$): m establishes the rate of decrease in strain rate with time; α gives the dependence of strain rate on stress level; A is the extrapolated strain rate at a reference time for a stress level of 0; t is time, and t_1 the reference time.

Mitchell (1976) reviews some of the procedures which have been used to predict when creep rupture will occur. Some of these assume that the product 'strain rate-time' is constant, others attempt to correlate the time required to reach minimum strain rate with the time to failure.

None of these methods give a complete picture of creep behaviour from primary through to tertiary. Ting (1981; 1983a; b) did this, developing the Assur-Ting model (strain rate = $Ae^{\beta t}t^{-m}$), where m, as before, establishes the rate of decrease in strain rate with time; m establishes the rate of decrease in strain rate with time; β gives the dependence of strain rate on stress level; A is the extrapolated strain rate at a reference time for a stress level of 0; and t is time. The approach basically represents a nice curve-fitting technique.

3.2 *Creep susceptibility*

Singh and Mitchell (1969) regard the parameter 'm', describing the rate of decrease in strain rate with time, as a property which is closely related to the "creep potential" of a material. Lower values of m mean that the strain rate decreases at a slower rate than when m is larger. Ice and frozen sand, which are highly creep susceptible (i.e. most of the strain occurs after the load has been applied), have low values of m (about 0.5 ± 0.1 compared to 0.5 to 1.3 for clays). However, another extremely important factor is the absolute magnitude of the strain rate imme-

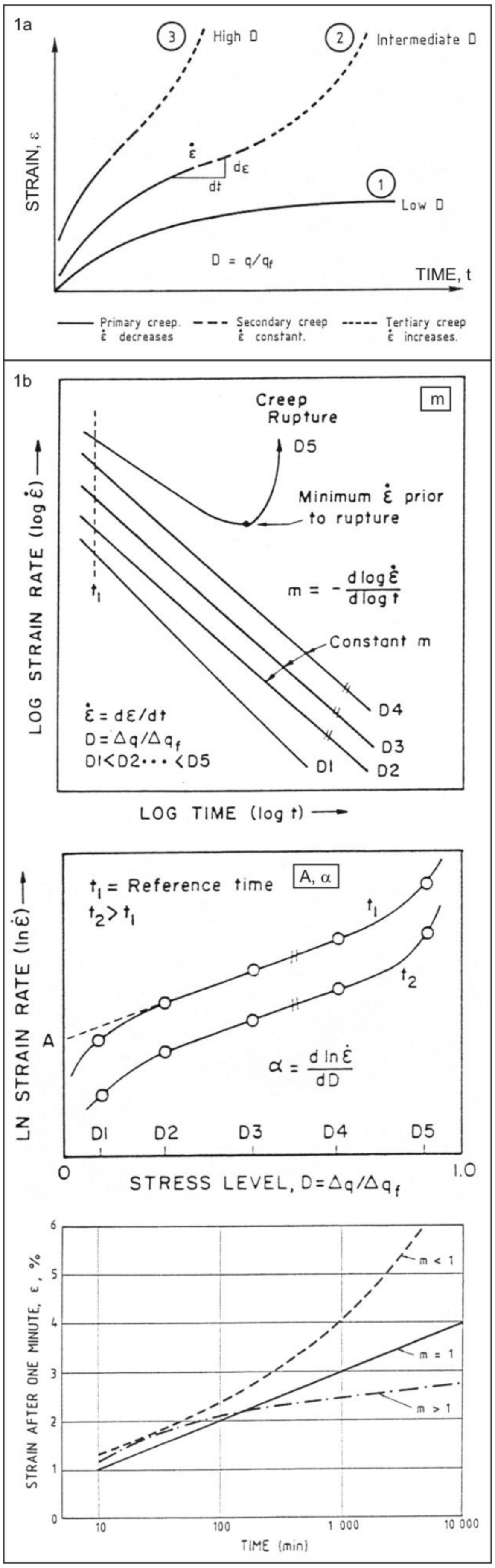

Figure 1. Basic creep behaviour from constant stress undrained creep testing on soft clays (after Mitchell, 1976)

diately after load application, described by the strain rate at a time of one minute as a function of the stress level D. The more creep susceptible materials have a higher strain rate at a given stress level D than less creep susceptible materials. Specifically, simple shear creep tests on the highly creep susceptible Atchafalaya levee clay plot above and to the left of the "well behaved" Haney clay and the three clays all plot well below frozen materials. Hence, where a material falls in a diagram of strain rate and stress level as well as the value of m should be considered in evaluating the creep susceptibility of a clay.

4 LABORATORY RESULTS

Research results on creep of frozen sand are used for comparison, since the data are much more comprehensive than exist for undrained creep of clays and the trends are believed to also apply to clays.

4.1 *Test program*

Clay A from two layers was tested. The plasticity index of the clay was 41% above a depth of 24 m and 20% below 24 m. The 8 direct simple shear (DSS) tests were consolidated to the *in situ* effective stresses (p'_o) and applied shear stress levels between 45 and 98% of the static undrained shear strength of the clay. The creep loads were applied for 15,000 minutes under constant volume conditions. The three triaxial (CK_oU) creep tests, consolidated to p'_o and $K_o p'_o$ (with K_o=0.6) were run with shear stress levels ($\Delta\tau_{creep}/(s_u-\tau_c)$) between 40 and 90%. The creep loads were applied for over 20,000 minutes.

4.2 *Creep parameters*

Figure 2 illustrates the creep parameters m, A and α obtained from simple shear and triaxial tests used in Mitchell's (1976) rate process equation (strain rate = $Ae^{\alpha D}(t_1/t)^m$).

The rate of shear strain increases with shear stress level. The slope of the rate of shear strain versus time curve on log-log scale is approximately constant (parameter 'm'). At intermediate shear stress levels D, the strain rate appears to be vary linearly with stress level. The laboratory data present some scatter, mainly due to the stress level range used to select the reference undrained shear strength. The data however enable one to establish a best estimate of the creep parameters. These are listed in Table 1.

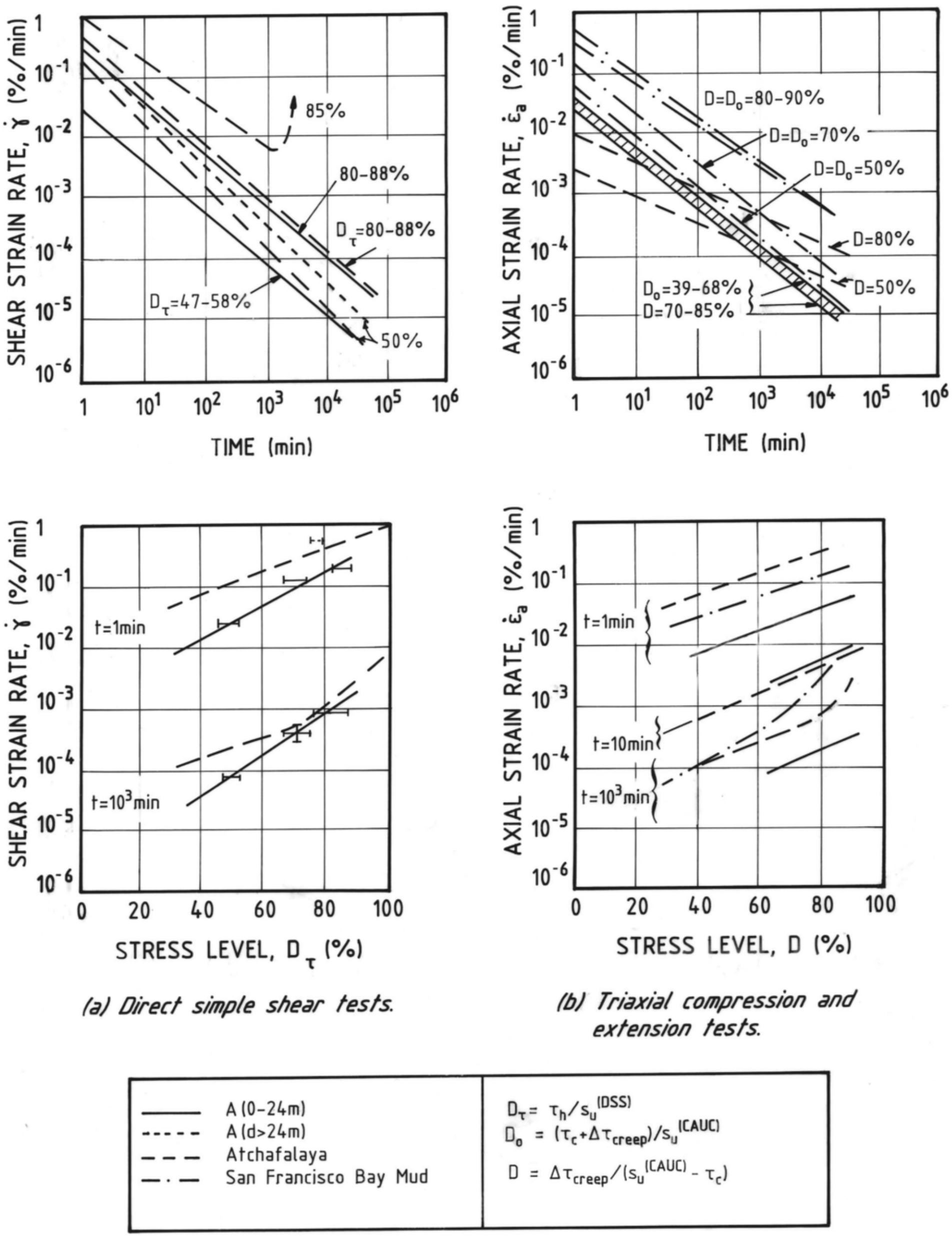

Figure 2. Results of triaxial and simple shear undrained creep tests on three clays.

Table 1 Creep parameters for different clays (OCR= 1-1.3)

Clay	m	α	A (min^{-1})
SF Bay mud (I_p = 52%)			
CIUC	0.73	5-7	0.9 x10^{-5}
Haney clay (I_p = 18%)			
CKoUC	0.80	-	-
CIUC	0.5-0.85	-	-
Atchafalaya (I_p = 55-85%)			
DSS	0.7-0.9	5	0.2 x10^{-4}
CKoUC	0.5-0.6	5	-
CIUC	0.5-0.8	6	-
Clay A, Norway (<24m)			
DSS	0.89	5-7	1.5 x10^{-5}
CKoUC	0.80	5	1.5 x10^{-5}
Clay A, Norway (>24m)			
DSS	1.02	-	-

Notation:
OCR overconsolidation ratio
CIUC isotropically consolidated triaxial compression test
CKoUC K_o-consolidated triaxial compression test
DSS direct simple shear
A, m, α undrained creep parameters, see definitions in text

5 CREEP SUSCEPTIBILITY DIAGRAM

5.1 *Creep susceptibility*

The effects of strain rate or rate of loading on undrained shear strength increase with plasticity. Undrained creep also increases with increasing plasticity. The manner a clay is affected by strain rate or rate of load application can be a first indicator of the potential for creep in a clay. The effects of strain rate are addressed in detail in the literature (e.g. Vaid and Campanella, 1974; Lacasse, 1994) and are not described further here, even if the effects can be very significant. Figure 3 illustrates some of the results for a number of normally consolidated clays. Accounting for these effects is very important, especially for rapid rates of loading. Similar effects are seen for overconsolidated clays.

To estimate the likelihood that undrained creep may occur, a creep susceptibility diagram was developed with well-documented data on clays and sands. This diagram is shown in Figure 4. The data come from Ting (1983a; b), Edgers *et al.* (1973), Fuleihan and Ladd (1976), Germaine and Ladd (1986), Kavazanjian and Mitchell (1980) and Campanella and Vaid (1974). The stress ratio is defined as the applied shear stress

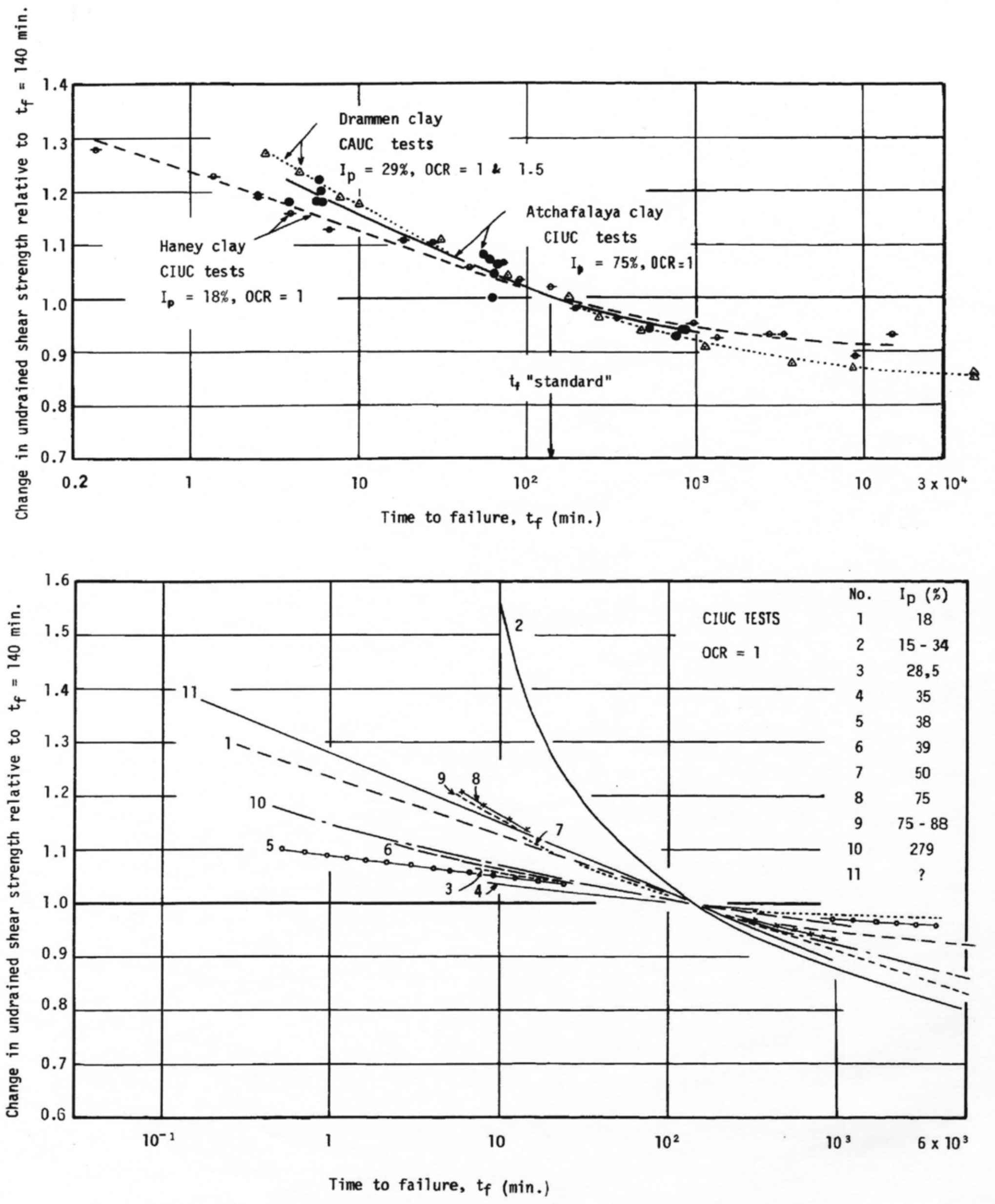

Figure 3. Effect of time to failure on undrained shear strength of normally consolidated clays (Lacasse, 1995).

divided by the shear stress at failure in %. The parameter S for frozen sand is the percentage of ice saturation in the sand (S = 40% and 100% in Fig. 4). With these results, it is possible to suggest a zone where clays are highly creep susceptible, and where they are not creep susceptible.

5.2 *Prediction of undrained creep in practice*

With foundations on clay and low safety factors, the effects of strain rate and creep need to be addressed. Detailed predictions of undrained creep deformations were compared to field data for the Atchafalaya levees (Edgers *et al.*, 1973). They attempted to use a linear visco-elastic finite element model, but the soil was too creep susceptible and modelling of only a few months behaviour was possible, although many years would have been required. Edgers *et al.* then used a finite element program with bilinear and hyperbolic stress-strain formulations to predict deformations versus time by inputting different stress-strain curves to account for creep via the Singh-Mitchell relationship.

Although a fairly extensive set of triaxial and simple shear creep tests had been run to measure the creep parameters A, α and m (Table 1), these parameters could not be used directly since it was unclear how to select a reference time and hence a reference strain rate A. The field lateral deformation data at the end of construction yielded values of α significantly less than measured in the laboratory creep tests. Hence the predictions were made using "field" values of A and α, laboratory values of m and stress levels from the finite element analysis.

The predicted and measured lateral deformations using the above procedure were in reasonable agreement, and this approach was used to predict the beneficial effects of installing vertical drains to accelerate the rate of consolidation (Fuleihan and Ladd, 1976).

Since the creep potential of a clay is related to the parameter 'm' but not uniquely, the following steps are proposed to evaluate the creep susceptibility of a clay:

- Compare the value of the m-parameter for different stress systems (test types) and various clays.
- Compare the creep parameter A (strain rate at unit time one minute) and α (strain dependence on stress level).
- Plot the strain rate upon load application vs shear stress level on a creep-susceptibility diagram (Fig. 4).
- Compare the normalised Young's secant modulus from undrained creep tests (versus time) and conventional static tests.

6 SUMMARY

The paper reviewed the components of settlement and essential aspects of undrained creep in clays. The undrained behaviour was described in a creep susceptibility diagram that can be used to evaluate the creep susceptibility of other clays. Undrained creep is of concern when the safety factor of structures on clays is low, when the foundation clays is thick and the coefficient of consolidation is low. The creep potential of a clay is related to the parameter 'm' (establishing the rate of decrease in strain rate with time), but not uniquely. The following steps are suggested to evaluate the creep susceptibility of a clay:

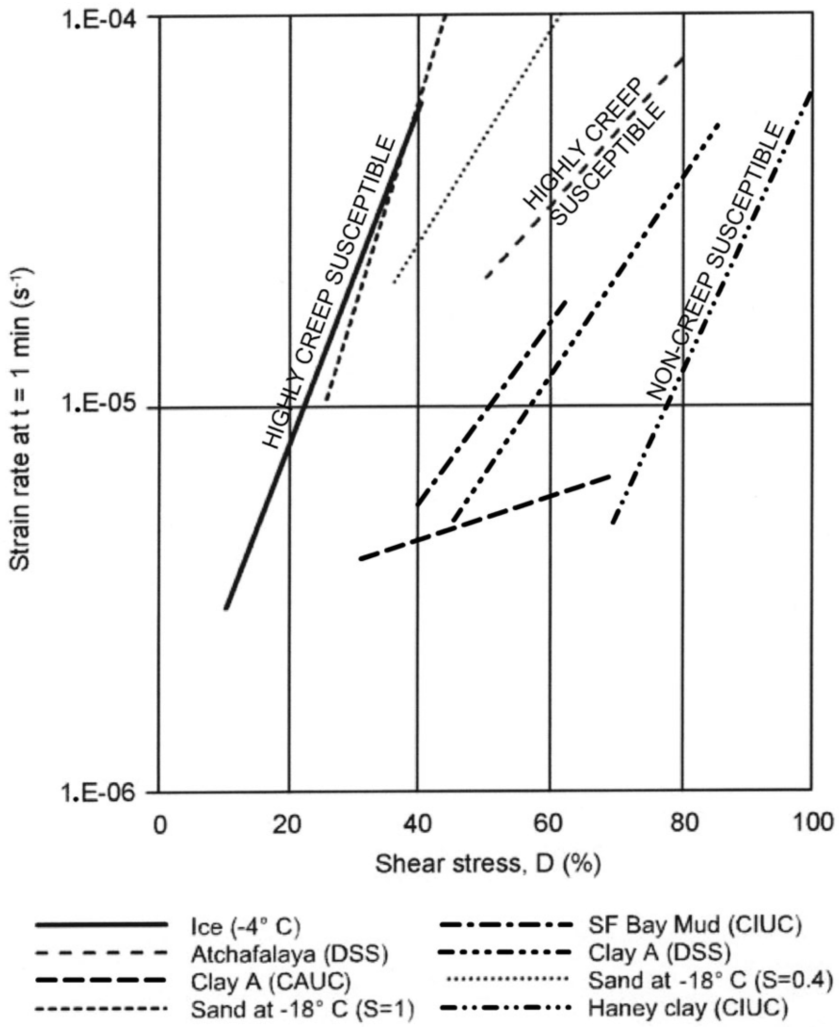

Figure 4. Creep susceptibility diagram

- Compare the value of the m-parameter for different stress systems (test types) and different clays.
- Compare the creep parameter A (strain rate at unit time one minute) and α (strain dependence on stress level).
- Plot the strain rate upon load application on a creep-susceptibility diagram (Fig. 4).
- Compare the normalised Young's secant modulus from undrained creep tests (versus time) and conventional static tests.

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