Temperature effects on consolidation properties of sulphide clays

Les effets de la température sur les propriétés de consolidation des argiles contenant des sulfures

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SYNOPSIS: When heat energy is stored in clay, the geotechnical properties will change as a result of changing temperature. This paper presents results from laboratory tests on sulphide rich silty clays. The tests are ordinary oedometer tests and creep tests in the temperature range 5 to 55°C. It is shown that even a small deviation of the testing temperature from the in situ temperature is of importance for the results. Based on the test results, a creep-temperature equation is proposed.

1 INTRODUCTION

In the coastal regions of northern Sweden sulphide-rich silty clays with water contents as high as 100 to 150% are widespread. Since water has a higher heat capacity than the mineral, a concept has been put forward to use this type of soil for heat energy storage. It is, therefore, of vital interest to investigate the influence of the storage process (heating and cooling) on the soil properties. In this paper, laboratory tests with respect to compression characteristics and long-term creep properties at raised temperatures of sulphide-rich silty soils are presented.

Among the tests performed are oedometer tests at different temperatures determining the influence of temperature on the preconsolidation pressure. This, however, is strongly dependent on the testing technique (Crawford 1964). In Fig. 1, the relation between vertical effective pressure and deformation in an oedometer test is shown. The consolidation time for each loading step has been 7 days. It can be seen that in this case there is a very large discrepancy between the preconsolidation pressures evaluated from "primary compression and from 7 days of loading.

This phenomenon has been described (Bjerrum 1967) in terms of instant and delayed compression. According to this concept, a clay which has undergone delayed, or secondary compression, is an "aged" clay. This means that the clay has developed a reserve strength and a quasi-preconsolidation pressure can be found when the sample is tested in an oedometer. In Fig. 1 this aging is represented by the dashed curve. For sulphide rich clays these secondary effects are very much pronounced in oedometer tests.

The preconsolidation pressure will be lower the higher the test-temperature is. In Fig. 2 oedometer tests, performed in the temperature range 5-45°C, are shown. This implies, that there is a similar mechanism determining the amount of creep at raised temperatures as the duration of the loading steps at in situ temperature. The creep, at a certain temperature and for a certain time, can thus be simulated in laboratory tests by raising the temperature during a shorter period of time.

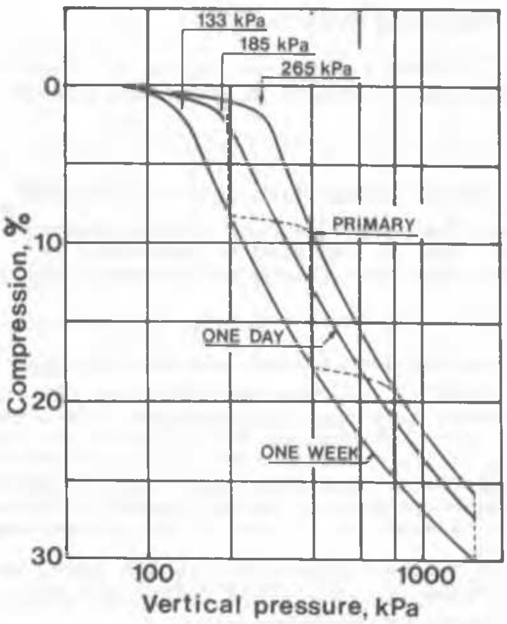

Figure 1. Preconsolidation pressure evaluated from primary compression, 1 day and 7 days of loading, after Crawford, 1964.

2. THEORETICAL BACKGROUND

If a consolidation test is presented in terms of the logarithms for the deformation rate, ε, and the time, t, cf. Fig. 8, the first part of the curve should, according to the classical consolidation theory, be linear with a slope of 1:2. This gives the linear relation

$$\log \dot{\varepsilon} = \log \dot{\varepsilon}_1 - 0.5 \log t \tag{1}$$

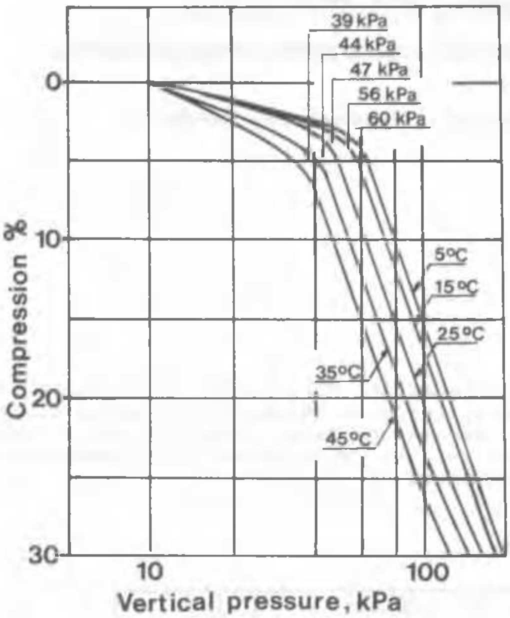

Figure 2. Oedometer tests performed on "identical undisturbed" samples at different temperatures.

where $\dot{\varepsilon}_1$ is the deformation rate at the time $t = 1$ min. The second part of the compression curve, cf. Fig. 8, can also be described by by a linear relation (Singh and Mitchell 1968)

$$\log \dot{\varepsilon} = \log \dot{\varepsilon}_b - m \log t/t_b \qquad (2)$$

where $\dot{\varepsilon}_b$ is the deformation rate at the intersection point of the compression curves (1) and (2) and where m is the Singh-Mitchell creep parameter which is determined from a triaxial creep test, Fig. 3. If the deformation follows the theoretical primary consolidation curve, the deformation-time relationship can be represented by a curve with a slope of 1:2 up to 50% primary consolidation.

A method has been presented (Parkin 1981) where the time-factor T_v is plotted versus the consolidation rate $\dot{U}$. By matching data from a test with this theoretical curve, the coefficient of consolidation, c_v, can be determined. Thus, at a matching point $\dot{U}_{ij}$ the degree of consolidation U_{ij} and the deformation ε_{ij} can be calculated. From this the total primary consolidation can be determined.

The total deformation can be calculated by integrating the sum of the equations (1) and (2). For $t \geq t_0$ and $m \neq 1$ this gives

$$\varepsilon = \varepsilon_1 + 2\dot{\varepsilon}_1(\sqrt{t_b} - 1) + C\dot{\varepsilon}_b(t^{1-m} - t_b^{1-m})/(1-m) \quad (3)$$

For m=1 the expression

$$\varepsilon = \varepsilon_1 + 2\dot{\varepsilon}_1(\sqrt{t_b} - 1) + C\dot{\varepsilon}_b \ln(t/t_b) \qquad (4)$$

is instead obtained. Here ε_1 is the total deformation and $\dot{\varepsilon}_1$ the deformation rate at t=1 min.

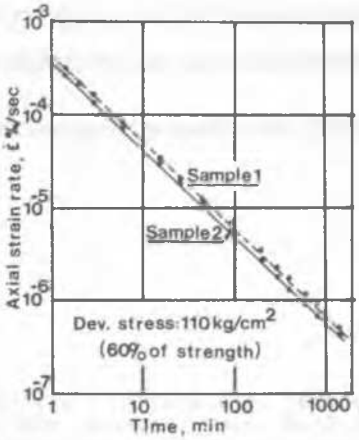

Figure 3. Strain rate versus time relationships during creep. (Singh & Mitchell, 1968).

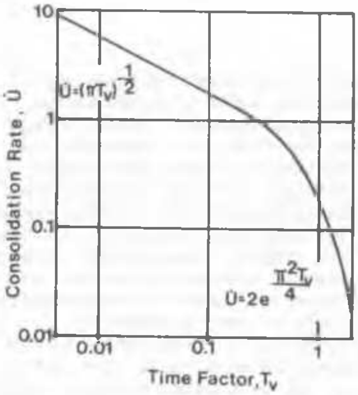

Figure 4. The Terzaghi consolidation time factor T_v vs consolidation rate U, Parkin, 1981.

Further, C is a constant depending on the intersection point of the two linear parts of the compression curve.

3 LABORATORY TESTING

The material tested is black sulphide-rich silty clay with some organic content. Long-term creep tests are performed on material from Kalix and the other tests on material from Luleå, both places situated in the northern part of Sweden. The soils are shortly described in Table 1.

Table 1. Soil properties of the materials tested.

	D	ϱ	w	w_L	w_p	τ_{fu}	S_t
	m	t/m³	%	%	%	kPa	
Luleå	4	1.40	110	110	50	24	14
Kalix	6	1.41	105	103	37	22	11

The ignition loss is for both materials 7%, and about 1/3 of this is organic content.

3.1 Compression tests at different temperatures

Standard stepwise oedometer tests have been performed for the temperature range 5-55°C with a loading ratio of 2 and with a loading increase every 24 hours. As can be seen in Fig. 2, there is a considerable difference between the preconsolidation pressure determined at the in-situ temperature, 5°C, and at normal room temperature, 20-25°C, at which temperature tests normally are performed. This sensitivity to temperature can be of importance when energy is stored in clay deposits.

Fig. 5 shows the preconsolidation pressure, σ'_c as a function of the test temperature. At 5°C, σ'_c is 60 kPa and decreases with 8 kPa/10°C. For temperatures above 45°C, the compression curve are difficult to interpret, but there is a tendency that the preconsolidation pressure asymptotically reaches the value 30 kPa for increasing temperatures. This pressure is very close to the in situ vertical effective pressure. This limit value for high temperatures has also been observed in another test series where Constant Rate of Strain tests were performed (Eriksson 1984).

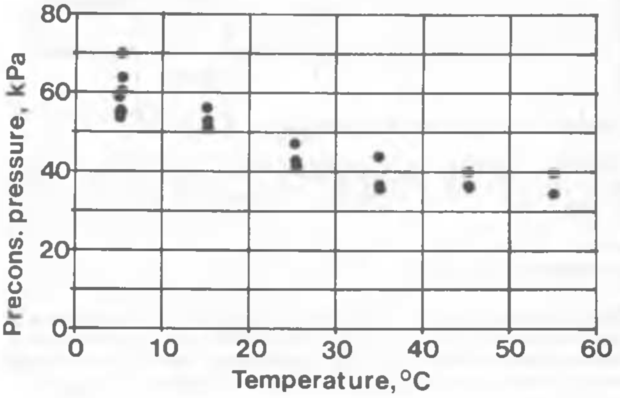

Figure 5. Preconsolidation pressure for the Luleå sulphide clay as function of the testing temperature.

When heat energy is stored in a clay deposit, a combined effect of creep due to time and temperature will occur. Another effect in a heat storage is that changes in the temperature will occur during loading and unloading. These changes will cause deformation, depending on different response from the water and the mineral particles due to different coefficients of thermal expansion. This consolidation is faster than the creep but does not change the total deformation. The cyclic loading, heating, and cooling of an energy storage will by itself cause some deformation due to different coefficients of thermal expansion, but the main effect is the thermal creep and time.

3.2 Creep tests at different temperatures

In order to find a relationship between stress, deformation, temperature and time, creep tests were performed at temperatures between 5 and 45°C. The tests were standard oedometer-tests with a loading time for each step of 16 days. By plotting the results in a log-log scale, the creep parameter m can be determined. In Fig. 6 the parameter m for a test at 5°C is shown for the stress range 40 to 320 kPa. As can be seen, there is a certain scatter, but there is a clear tendency that the mean value of m is very close to 1.0. For a natural soil sustaining creep, the maximum sensitivity to creep deformations should be in the stress intervall above σ'_c. For stresses below σ'_c, the soil has already sustained creep (delayed compression). For stresses well above the preconsolidation pressure, the soil will start to behave strain hardening, thus decreasing the amount of creep. In the tests shown in Fig. 6, there is only a small maximum (a low m-value, which means a higher rate of creep) around 80 kPa ($\sigma'_c \approx 60$ kPa), but examining the whole range of stress, this can only be interpreted as scatter. However, in Fig. 3 there is a vague tendency that the creep rate is somewhat higher just above σ'_c (in this case ≈40 kPa). However, results from oedometer tests have been shown (Parkin 1981) where there is a clear maximum in creep rate close to the preconsolidation pressure.

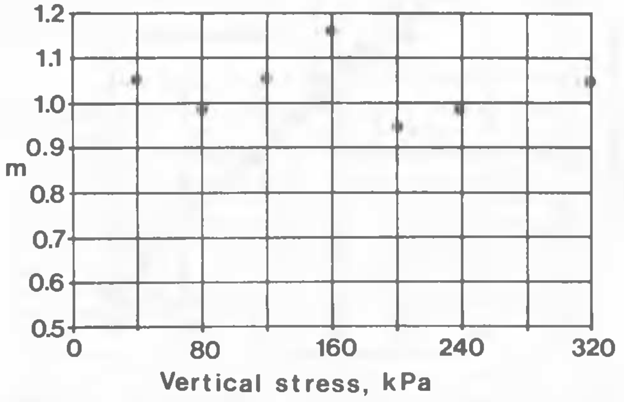

Figure 6. The creep parameter m from oedometer tests at 5°C at different vertical effective stresses.

For the investigated range of tempeature, average values of the creep parameter m have been evaluated for two tests at each level of temperature and for two to three levels of stress, Fig. 7. The diagram shows some scatter, but there is a clear tendency that the value of m decreases with increasing temperature.

The value of the creep parameter m is here for simplicity approximated by a linear function in the temperature

$$m = 1.03 - 0.0072T \qquad (5)$$

where T is the test temperature in °C.

3.3 Long term creep tests

Creep tests were also performed in triaxial cells at 5°C. The sample were surrounded by a rubber membrane and by steel rings to prevent lateral deformation. The distance between the steel rings were 0.5 mm to make vertical deformation possible

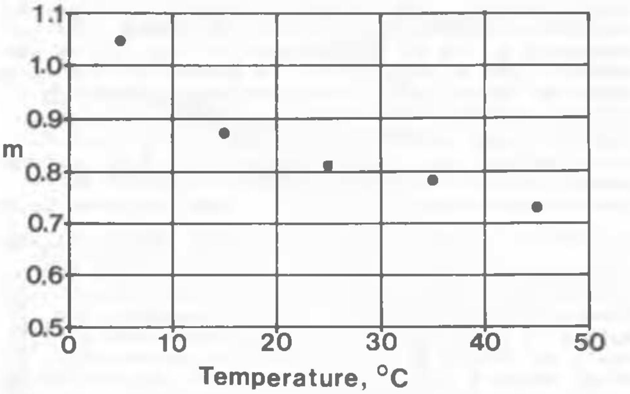

Figure 7. The creep parameter m evaluated from creep tests in temperatures between 5 and 45°C.

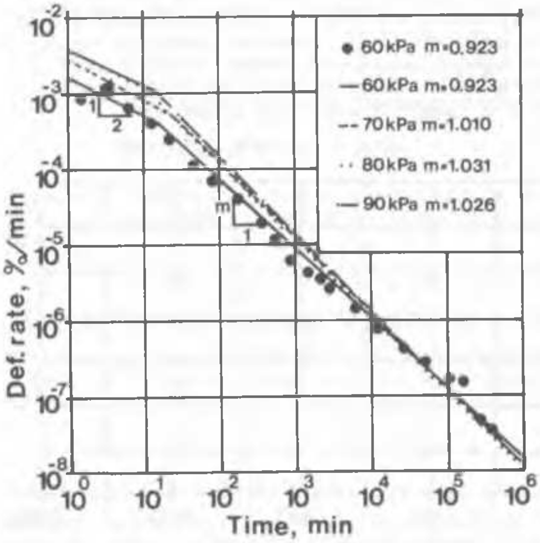

Figure 8. Relation between deformation rate and time for creep tests performed at different stress levels

without frictional losses. The samples were consolidated for a vertical pressure σ_1 = 40 kPa and for a radial pressure σ_3 = 20 kPa. Then σ_1 was increased to respectively 60, 70, 80 and 90 kPa in four different tests. It is convenient to present data from creep tests in a log-log scale, where the deformation rate is plotted against the time (Singh and Mitchell 1968). In Fig. 8, data from these four tests are presented. Detailed data from one test is shown, the other tests are represented by their linear regression curves. However, all four curves can be represented by two straight lines each, all with a correlation coefficient better than 0.992. The tests are still running (sept 1988) and are planned to continue as long as the test set up is working.

The creep equation (3) with the temperature-dependent creep parameter m according to eq. (5) yields a too large deformation after a relatively short time, when the test-temperature is increased. This indicates that the creep is linear only for a limited range of stress. As can be seen from Fig 2, this range in the lin ε-log σ diagram is considerable, which means that the equation (3) with m according to (5) is valid at least up to 35-40% of the deformation. Thereafter, the material starts to behave strain-hardening.

In Fig. 9 the strain-time-temperature relation according to eqs. (3) and (5) is illustrated. The diagram shows the creep deformation at 5°C, from 0.7 days to 200 years (dotted lines). If the creep tests are performed at higher temperatures, the results will be as shown by the dashed lines.

From Fig. 9, it can also be seen that the creep gives rise to 5% deformation after 70 days at a test temperature of 5°C. If the creep test instead is performed at room temperature the deformation of 5% is reached already after one week. For a temperature of 40°C, this deformation is reached within one day.

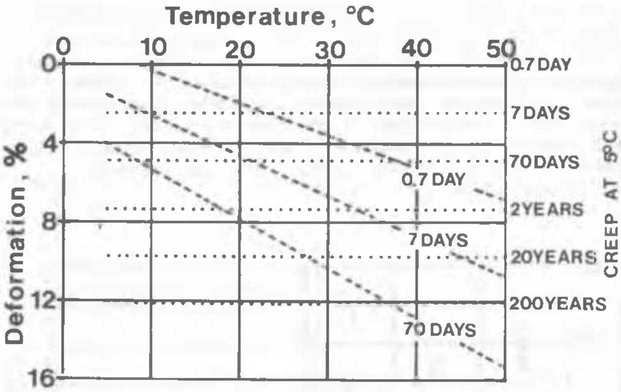

Figure 9. Creep deformations for sulphide clay determined from equation (3) with m according to (5)

4. CONCLUSIONS

When heat energy is stored in a soil formation, considerable deformation might take place. For the sulphide rich-clays examined, the laboratory tests show that the deformation due to raised temperatures is of the same nature as for long term creep. It is possible to take this temperature creep into account when long term creep is determined, as shown in the discussed creep equation. It has also been shown, that the relation between the laboratory temperature and the in situ temperature is of utmost importance when testing sulphide-rich soils.

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