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ORIGINAL PAPER

Determination of Creep Properties of Clays from VRS Oedometer Tests

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Abstract The determination of creep properties still relies almost entirely on the incrementally loaded oedometer test introduced about 100 years ago. Although the simplicity of the test assures a robust evaluation of soil parameters, it also introduces some shortcomings like discontinuity of the evaluated parameters and the long duration of the test. In this study, the performance of the variable rate of strain (VRS) oedometer test for determination of creep properties of a sensitive soft clay is studied. The results from a comprehensive test series of VRS oedometer tests on a soft sensitive clay is presented. Three different setups for the strain rate variation were used, and each test was repeated thrice. The tests showed good consistency and yielded equal creep parameters compared to values from traditional incrementally loaded (IL) oedometer tests. The tests further verified that it is possible to describe the complex stress dependency of creep parameters with just one additional parameter to the primary deformation parameters. Compared to the IL tests, the VRS tests offers a faster determination and continuous creep properties for a wide range of stress.

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1 Introduction

The estimation of creep deformations composes a vital part of settlement analysis of soft clays, as suggested by the important works of Šuklje (1957), Bjerrum (1967), Janbu (1969), Leroueil (2006) and more recently Grimstad et al. (2017). It is thus important to be able to determine the creep properties reliably and preferably within a reasonable timeframe. The determination of creep properties relies still almost solely on the incrementally loaded (IL) oedometer test, which was introduced about 100 years ago. The principle of the determination of creep properties from IL oedometer tests is simple and solid. A drawback of the method is that creep properties are derived only from preselected stress levels. In addition, it takes a lot of time to determine the creep properties for a wide stress range.

As an alternative, Länsivaara (1999) introduced the variable rate of strain (VRS) test. Although good results have been observed for both Norwegian clay (Länsivaara 1999) and Finnish clay (Pedreño 2006), the VRS test has not been widely adopted. This paper presents results from a comprehensive test series,

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where creep properties determined from VRS tests at the geotechnical laboratory of Tampere University were compared to those determined from IL oedometer tests at Aalto University (Mataic 2016). To ensure the quality and repeatability of the VRS tests, each test was repeated thrice.

2 Factors Influencing the Stress–Strain Behaviour of Sensitive Clays

To discuss the behaviour of sensitive clays in oedometer tests, and how engineering properties vary during the tests, it is helpful to first review the factors that influence the stress–strain behaviour of such clays.

In favourable conditions, interparticle flocculation before sedimentation produces an open structure that can retain more water than when the particles are not flocculated before settling (Torrance 2014) (Fig. 1a). For marine clays, the salty water reduces the repulsive forces between the negatively charged particles, allowing flocculation. For freshwater clays, the presence of cations such as calcium have a similar effect. The flocculation may be prevented by rapid deposition from dense suspension. Similarly, flocculation will not occur for reconstituted samples where the water content is normally below 1.5 times the liquid limit; while, if a very high-water content is used to form the slurry, evidence of flocculation can be found (Burland 1990).

The impact of stress history is perhaps the most obvious of the various factors, as the clay consolidates to a denser state along the virgin consolidation line. Surface erosion or fluctuation in ground water level reduces the effective stresses in the soil, resulting in a stress-induced overconsolidation (Fig. 1a).

With time, the void ratio of a clay decreases, even though effective stresses remain constant. The creep, also known as ageing, provides the soil with additional resistance against further loading, which can be viewed as a time-induced quasi overconsolidation in the oedometer test (Fig. 1b).

Interparticle bonding, also known as cementation, cause additional hardening of the clay. Many minerals have been proposed to act as cementing agents, but recently Torrance (2012) argued that iron oxides are the only potential cementing agents that exist in sufficient quantity to be effective (Torrance 2014). Cementation causes relatively strong but brittle bonds between the particles. This give the clay a form of additional resistance, which can also be seen as quasi overconsolidation in the oedometer tests. When the stresses exceed the preconsolidation pressure, the structure collapses, resulting in very low stiffness until the virgin compression line is reached (Fig. 1c).

For marine clays leaching, i.e. displacement of the salty pore water by freshwater has a large impact on the behaviour, as the repulsive forces between the clay particles increase. The original flocculated structure and water content remains, but the liquid limit often decreases well below the water content. Thus, when the structure is destroyed, as when passing the preconsolidation pressure, the clay cannot withstand the high-water content; large deformation occurs until the compression line corresponding to the new pore water chemistry is reached (Fig. 1d). Similarly, the remoulded strength reduces, and after reaching a certain threshold, the clay classifies as quick clay.

In Fig. 1, the different factors discussed above are illustrated as individual occurrences, although they occur as combination of some or all. In practice, it is quite impossible to distinguish between them just by looking at the stress strain curve from the oedometer. For example, large deformation with very small stress increases immediately after passing the preconsolidation pressure, which is typical for sensitive clays—probably the result of cementation or leaching or both. In Fig. 2, an example of a history plot for a soft sensitive clay is presented. The clay has sedimented in salty water, allowing for flocculation of the particles. The clay has then been consolidated by its own weight up to point A. Thereafter, creep has reduced the void ratio during hundreds and thousands of years leading up to point B. In further loading, the clay is first showing a stiff response, as ageing and cementation has resulted in a quasi overconsolidation up to the yield stress at point C. During the clay's history, leaching has occurred, resulting in the virgin compression line lowered to correspond to the new pore water chemistry. As a result, large deformation occurs, passing the yield stress, as the soil body collapses due to breaking of the cementation bonds, and as the soil body cannot withstand the open structure anymore, until a new virgin compression line is finally reached at D, which corresponds to the leached salinity of the pore water. Afterwards, the clay may be subject to

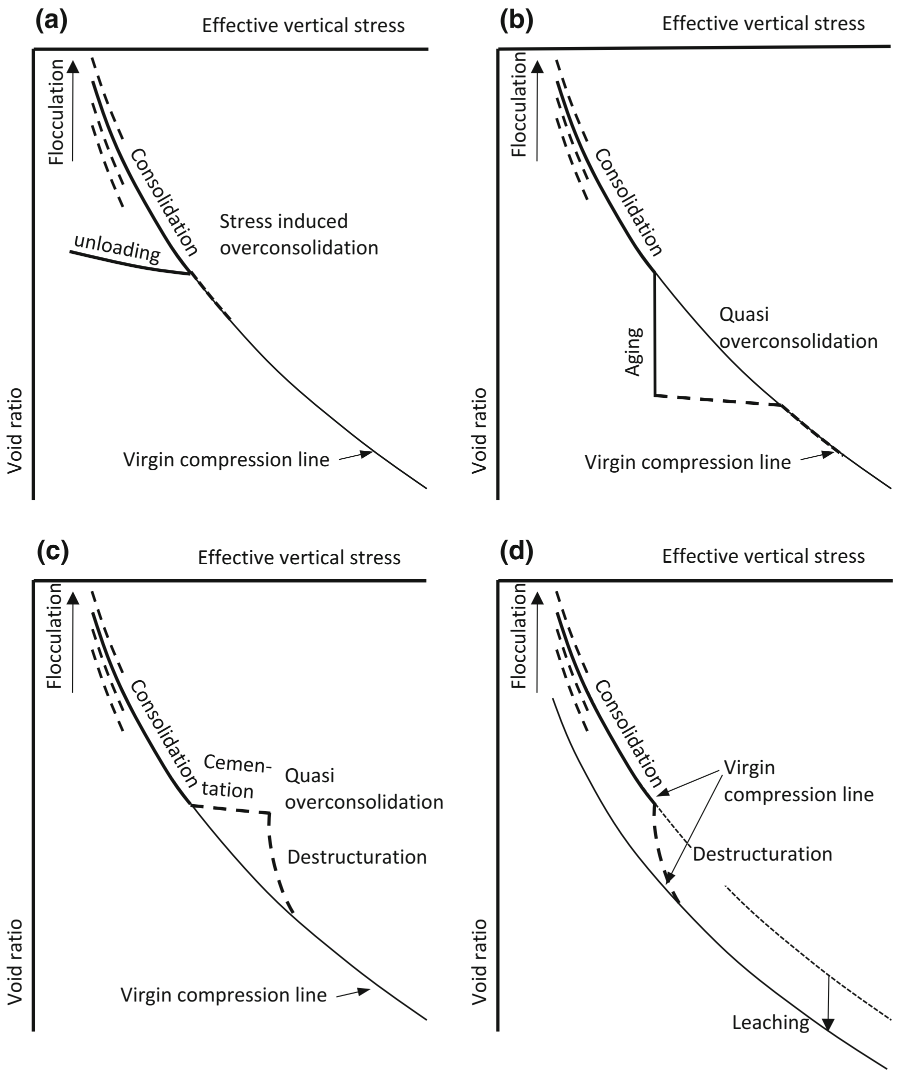

Fig. 1 The influence of inherent factors such as **a** flocculation and consolidation, **b** aging, **c** cementation and **d** leaching on the deformation behaviour of soft clays

further ageing, loading/unloading, and changes in pore water chemistry.

3 Stress–Strain Behaviour Observed in the Oedometer Tests

The complicated stress–strain–time behaviour of clays is inevitably influenced by the choices people make, deliberately or unintentionally, in testing. It is well known that sample quality highly affects the obtained stress strain behaviour. With increased sample disturbance, the initial stiffness and obtained preconsolidation pressure decreases, while the behaviour just after passing the preconsolidation pressure is less collapsible. Especially, cementation effects can easily be destroyed by poor sampling. In addition, when the clay content decreases, the number of bonds also decreases and the soil becomes more vulnerable to disturbance. The choice regarding the type of testing, e.g. using an incrementally loaded (IL) oedometer test or continuously loaded with a constant rate of strain (CRS) oedometer, especially the loading/strain rate, greatly influences the test results, particularly the preconsolidation pressure (Sällfors 1975; Leroueil et al. 1983, 1985; Länsivaara 1999). Faster loading yields a higher preconsolidation pressure.

The interpretation of stress strain behaviour in oedometer tests is commonly carried out by applying a separate model for the stress–strain behaviour and

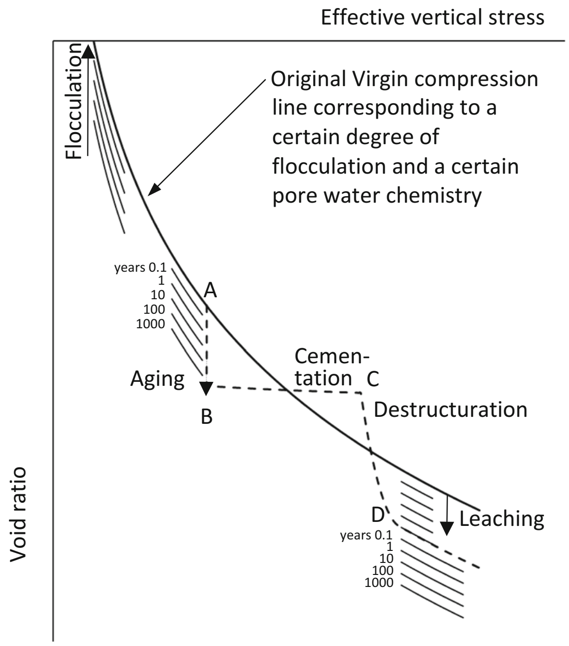

Fig. 2 A principal history plot showing the consequences of various phenomenon to the effective stress void ratio relationships of soft sensitive clays

another model to account for the creep/viscous behaviour; although it is good to bear in mind that the viscous nature of clay is always present. Thus, the pure stress–strain behaviour and the model parameters applied are also influenced by the time/rate conditions during the test. Internationally, the compression index C_C is widely used to describe the stress strain behaviour in oedometer conditions. For a long time, the compression index has been defined as the slope of a constructed line in an e−logσ_v' diagram. It is perhaps good to remember that in the early works by Terzaghi and Casagrande, C_C was used for the slope of the measured e−logσ_v' and not for an average constructed slope (Janbu 1998).

In the Scandinavian countries, the constrained modulus M is commonly modelled using the formulation by Janbu (1963) or Sällfors (1975). The development of these models was partly initiated by the fact that the compression index method could not always accurately describe the stress strain behaviour of soft and sensitive Scandinavian clays. The most commonly used equation by Janbu for the constrained modulus is written as follows:

$$M = m \cdot \sigma_a \left(\frac{\sigma'_v}{\sigma_a} \right)^{1-n} \tag{1}$$

where m is the modulus number, n is the stress exponent, and σ_a is a reference stress equal to 100 kPa. If the stress exponent $n = 0$, the modulus becomes linearly dependent on the effective stress, and there exists a simple relationship between the modulus number and the compression index which is as follows:

$$C_c = \frac{(1 + e_0) ln 10}{m}, (n = 0) \tag{2}$$

The model by Sällfors can be described with the aid of Fig. 3a. The constrained modulus is modelled in three parts, one for the OC region and two for the NC region. In the OC region, a constant modulus M_0 is used. After the preconsolidation pressure σ'_p, a constant modulus M_L is used until a limit stress σ'_L is reached, where after the modulus increases linearly with stress with the inclination M'. It should be noted that M' is not equivalent to m ($n = 0$) or C_C.

As described in the previous chapter, structured sensitive clays show a major drop in stiffness when the preconsolidation pressure is passed. After reaching the virgin compression line, the stiffness increases in a manner similar to non-structured clay. It is the experience of the author that this kind of behaviour can best be modelled with the Sällfors constrained modulus concept, allowing for the separation of the two phases.

To account for creep effects, secondary compression index is mostly used internationally. Therein a linear relationship is assumed in the final part of the consolidation phase in an e-logt diagram. In Scandinavia, the creep number r_s of Janbu (1969) is more often used. Therein the time resistance R is defined as follows:

$$R = \frac{dt}{d\varepsilon} \tag{3}$$

The time resistance R is thus the tangent to the strain–time curve. Note the resemblance to the constrained modulus (effective stress resistance $M = d\sigma_v'/d\varepsilon$). The time resistance R increases with time, and after a certain time, the increase is usually linear with respect to time. The slope of the R-t diagram is defined as the creep number r_s (Fig. 4). If this linear line intercepts with the origin, the definition

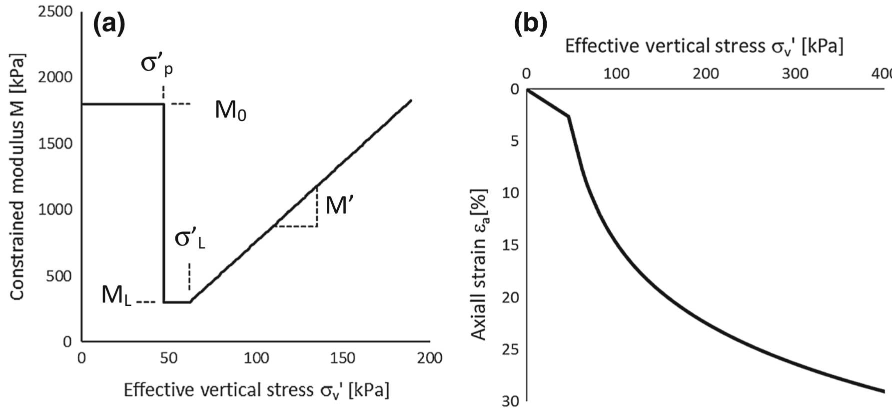

Fig. 3 The CRS model by Sällfors (1975) **a** definition of the model and its parameters and **b** example of resulting stress strain behaviour

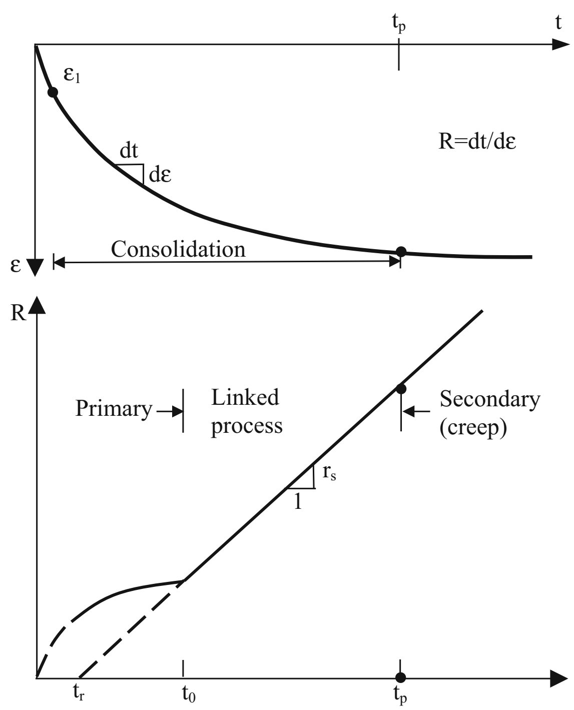

Fig. 4 The definition of time resistance R and creep number r_s for a constant load step in an IL oedometer test (replotted after Janbu (1998))

of the creep number becomes equal to the traditional definition of secondary compression index, and the relationship can be defined as follows:

$$C = \frac{(1 + e_0)ln10}{r_s} \tag{4}$$

However, as shown by Nash and Brown (2015) and by Grimstad et al. (2015), there are some underlying problems in using the time(log) presentation, as time is not an objective measure. In reality, the linear line in a time resistance R versus time plot does not necessarily intercept with origin. In such a case, the behaviour in a time(log) versus strain or void ratio plot will never be fully linear, and thus the C_α value will be dependent on the time intervals chosen. Instead, Nash and Ryde (2001) suggested the use of a strain rate versus strain plot to determine the creep properties. Such procedure will always provide consistent values compared to creep numbers determined from presentations such as Fig. 4, i.e. Eq. (4) is always valid (Grimstad et al. 2015).

Experimental results (Graham et al. 1983; Janbu 1998) show that both the secondary compression index and the creep number value depend on the stress. A low C_α value and a high r_s value can be found for stresses less than the preconsolidation pressure, while the highest C_α and lowest r_s values are obtained immediately after passing the preconsolidation pressure; after which, a slow decrease of C_α and a slow increase of r_s can be observed (Fig. 5).

Therefore, the experimental observations indicate that C_C and C_α are not constant, even only for the normally consolidated part of the oedometer test, while a clear stress dependency can be found. However, the ratio C_α/C_C or equally m/r_s is often reported to be constant for clay (Mesri and Godlweski 1977; Leroueil 2006). Mesri and Godlewski (1977) reported C_α/C_C values in the range between 0.025 and 0.10 for a variety of soils. Their data showed that the values were in general high for peats, somewhat less for organic clays, medium for some clays and organic silts, and small for some clays and silts. Mesri and Castro (1987) pointed out that when comparing the ratio, it is important to use a value of C_C corresponding

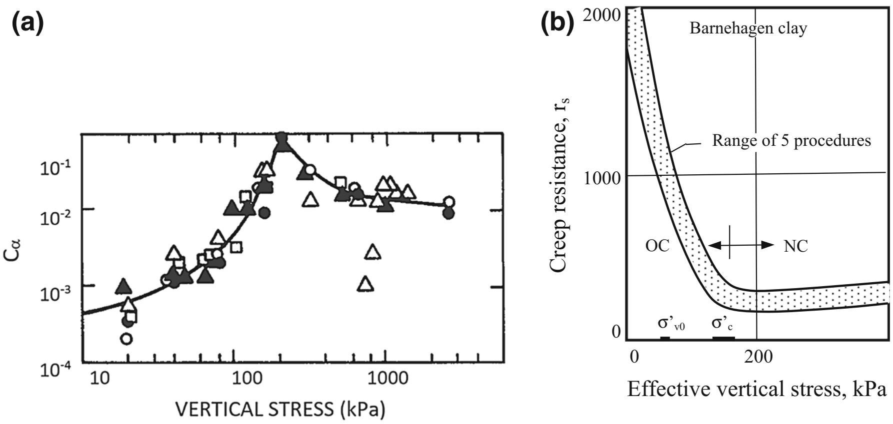

Fig. 5 The influence of stress and yield stress to **a** secondary compression index Cα on Ottawa Lacustrine clay Canada (Graham et al. 1983) and **b** creep number rs for Barnehagen clay, Norway (replotted after Janbu (1998)). The different symbols in Graham et al. (1983) corresponds to different loading procedures

to the stress state for which the value of C_α has been determined and not to use an average value. In addition, the data presented by Janbu (1998) on modulus and creep numbers support the connection of creep or viscous strain to primary strains.

4 The Variable Rate of Strain Oedometer Test

As discussed by Leroueil et al. (1985), oedometer stress–strain curves from tests conducted with different strain rates, and normalised by the preconsolidation pressure, coincide in a single curve. This follows the principles of the isotache approach (Šuklje 1957). As discussed by Leroueil (2006), the set of isotaches can be described by two curves: one giving the variation of the preconsolidation pressure with strain rate and the second the normalised stress–strain curve. In agreement with the previous finding, Länsivaara (1995) showed that the effective stresses (σ'_{v1}, σ'_{v2}) for the same strain from two tests conducted at strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are as follows:

$$\frac{\sigma'_{v1}}{\sigma'_{v2}} = \frac{\sigma'_{p1}}{\sigma'_{p2}} = \left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)^B \tag{5}$$

where σ'_{p1} and σ'_{p2} are the corresponding preconsolidation pressures, and B is the rate parameter defined as follows:

$$\frac{C_\alpha}{C_c} = \frac{m}{r_s} = B \tag{6}$$

It should be noted that for the equality to be valid in (6), the modulus number m must correspond to a stress exponent of $n = 0$, and the creep number r_s must be determined as the slope of the R-t diagram for a line going through the origin.

As relation (5) is true for stresses at any strain, this strongly indicates that the C_α/C_C ratio must be constant. This was further utilised by Länsivaara (1999) when introducing the variable rate of strain (VRS) tests. The basic idea of the VRS test is that the strain rate is varied between two values during the tests. The rate parameter B (or the C_α/C_C ratio) can then be directly determined from Eq. (5). To further determine the creep parameter C_α, one should first acknowledge that for $n = 0$, Eq. (1) is as follows:

$$M = m \cdot \sigma' \tag{7}$$

Then, an expression for the secondary compression index can be found, by combining Eqs. (2), (6) and (7), with the aid of an general tangential stiffness modulus M and the rate parameter B as follows

$$C_\alpha = \frac{(1 + e_0) ln 10 \cdot \sigma'}{M} B \tag{8}$$

It is important to emphasise the use of Eq. (7) in (8) in order to define the modulus number or compression index, as they should represent the incremental value and not an average value. This is equivalent to the previously discussed findings by Mesri and Castro (1987) which say that when calculating the C_α/C_C ratio for clay, one should use a C_C value corresponding to the stress level from which the C_α value has been determined and not an average value.

5 Previous Results

Länsivaara (1999) presented VRS oedometer results for a Norwegian clay, where the strain rate varied between $\dot{\varepsilon}_1 = 3.33 \cdot 10^{-6} s^{-1}$ and $\dot{\varepsilon}_2 = 3.33 \cdot 10^{-7} s^{-1}$. Creep numbers determined from the test corresponded well with creep numbers determined by Christensen (1985) via IL oedometer tests used for the same clay, as shown in Fig. 6. The bold line corresponds to the variation of creep number r_s in the VRS test, while the thinner line corresponds to the, extrapolation of the results using fitted constrained modulus and a similar expression to Eq. (8) for the creep number. Although there are scatter in the creep number values determined from IL tests, the average behaviour closely follows the VRS test results. Claesson (2003) performed VRS-tests on soft Swedish clays. He did not provide any B values calculated from his tests, but based on his results for Änggården clay at 7 m depth, a value of B equal to approximately 0.074 can be evaluated. Claesson concluded that the VRS method is not suitable for the Swedish clays as they do not follow a linearly stress dependent modulus. This conclusion seems merely based on the misunderstanding that a linearly stress dependent modulus would be required, while no attempt to determine the creep properties out of VRS tests were made. As explained previously, by applying Eq. (8), no assumption of the modulus needs to be made. The creep parameters C_α or r_s can be determined with the use of Eq. (8) (for C_α), using any preferred model for the constrained modulus.

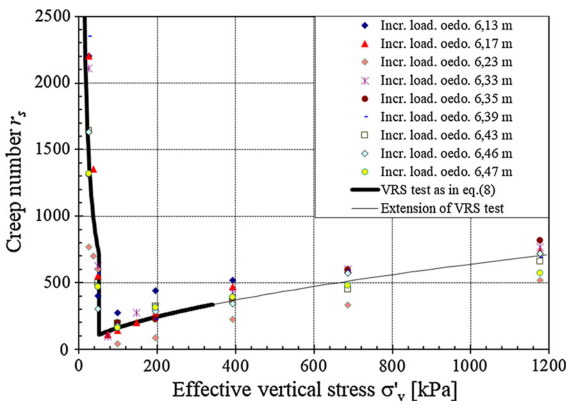

Fig. 6 Creep number r_s on a Norwegian clay from VRS oedometer tests and IL oedometer tests (Christensen 1985), data from Länsivaara (1999), data label modified for VRS tests

Pedreño (2006) presented results from various Finnish clays by comparing VRS test results to incrementally loaded oedometer test results. In general, the two tests produced very similar results, but a shift in the creep values could be obtained for some, although the trend with respect to effective stress changes were similar. No explanation for the differences were provided. Pedreno reported B values of order 0.045–0.067 for Naantali clay with a water content between 92 and 130%, and B = 0.051–0.072 for Turku clay with a water content between 76 and 94%

6 Comprehensive Test Series on Perniö Clay

To study the applicability of determination of creep properties out of VRS tests, a comprehensive test series for the sensitive Perniö clay from Finland was performed. The soft clay, below a 1.0–1.5 m thick dry crust layer, generally has a high-water content exceeding the liquid limit, a plasticity index in the range between 20 and 45%, and a sensitivity between 20 and 60. The organic content is generally less than 1%.

The samples were obtained with an Aalto 86 mm piston sampler, also referred to as a NGI 86 mm sampler (Mataic 2016). The 45 mm diameter oedometer samples were cut from the middle of the sample cross-section to ensure the best possible sample quality. The evaluation of sample quality using the Lunne et al. (1997) criteria is somewhat difficult, as the strain rate is varied. This also points out one problem with the criteria: the deformation required to reach the in situ effective vertical stress used in the criteria depends on the strain rate used. In a previous study on Finnish clays Di'Buo et al. (2018) concluded that the Aalto 86 mm piston sampler generally provided samples of good quality. The interpretation of the yield stress was based on fitting the Janbu constrained modulus (1963) and the Sällfors constrained modulus (1975) to the stress–strain curve, using the least square method for given stress ranges in the pre- and post-yielding regions. The preconsolidation pressure is then determined from the intersection of these lines (Kolisoja et al. 1989). Tests were conducted from three different depths, namely, 3.3–3.7, 5.4–5.7 and 6.3–6.6 m. To investigate possible differences in the samples, the water content was determined for all individual samples, while grain size distribution was determined for each series for the uppermost and lowest samples both combined with the middlemost sample.

Another issue studied was what strain rates and what relation between the strain rates should be used in a VRS test. When selecting the strain rates, at least, the following criteria needs to be fulfilled:

- The difference between the two strain rates needs to be adequately high, so that a well-defined difference between the effective stresses at a certain strain level can be found.
- The lowest strain rate should not be too slow to prolong the tests unnecessarily.
- The highest strain rate should not be too high, so that the average effective stresses for the oedometer sample can be determined reliably.

The final point is to some degree influenced by the interpretation theory used. Herein, the theory by Tokheim and Janbu (1976) is used, which accounts for the pore pressure/load ratio in calculating the average effective stress. According to Länsivaara (1994), this approximate solution provides an effective stress which is close to the exact solution when the pore pressure/load ration is less than 0.4. However, normally, the load/pore pressure ratio is often kept under 0.2. One should also consider that the higher strain rate and thus the pore pressure load ratio, the larger is the difference in effective stresses within the oedometer sample, could be seen as a more blurred preconsolidation pressure.

Three different set-ups for the strain rates were used. In all of them, the tests began with the highest strain rate, changing to the lowest at 2% deformation and changing every 4% of deformation after that. The selected strain rates are presented in Table 1. All tests were conducted thrice to study the repeatability of the tests, so a total of 27 VRS tests were carried out.

Table 1 Strain rates used for the three different test series

Strain rate s^{-1}	Test series		
	VRS1	VRS2	VRS3
High	1.67×10^{-6}	4.44×10^{-6}	1.11×10^{-5}
Low	1.67×10^{-7}	4.44×10^{-7}	2.22×10^{-6}

The tests have been previously partly reported by Länsivaara (2012). However, a detailed presentation of the results as well as their analysis is missing. Therefore, the VRS tests have been revisited and reported in detail, and the results have been compared to C_α values from IL oedometer test series reported by Mataic (2016). It is, however, good to note that the C_α values presented by Mataic have been determined from traditional time (log) plots. As discussed earlier, this might lead to a small deviation compared to creep parameters determined from a more general framework, such as the time resistance plot, strain rate versus strain plot, or the VRS test.

6.1 Tests from Depth 3.3–3.7

In Fig. 7, the stress–strain curves from 9 VRS tests from samples at depth intervals of 3.3–3.7 have been presented. In Fig. 7a three identical tests for the series VRS1 have been presented, and similarly in Fig. 7b, c three tests out of the series VRS2 and VRS3 have been presented respectively. As can be seen from the figures, the repeatability of the tests is generally very good, and the tests fall into a very narrow range. Some variation can although be found, especially for the VRS3 series. The samples were quite homogenous, but there existed some differences in the water content, as listed in Table 2. In all samples, the percentage of fines smaller than 0.002 were larger than 60%. The values of the strain rate parameter B evaluated from the tests are shown in Table 2 together with the sample data.

Out of the nine tests performed at two different strain rates, 18 preconsolidation pressures can be determined. The strain rate dependency of these preconsolidation pressure values is shown in Fig. 7d). The strain rate dependency of all the tests give a rate parameter $B = 0.076$, which is close to the values obtained from the individual tests.

For the determination of the secondary compression index C_α using Eq. (8), the Sällfors CRS modulus was used to present the compression modulus in the tests. The results are compared to C_α values determined independently (Mataic 2016) from IL oedometer tests. The IL test samples were from a depth of 2.6–2.7 m and were thus not exactly from the same depth as the VRS tests. However, the samples belonged to the same stratigraphic layer A, as defined by Mataic (2016). The water content of the

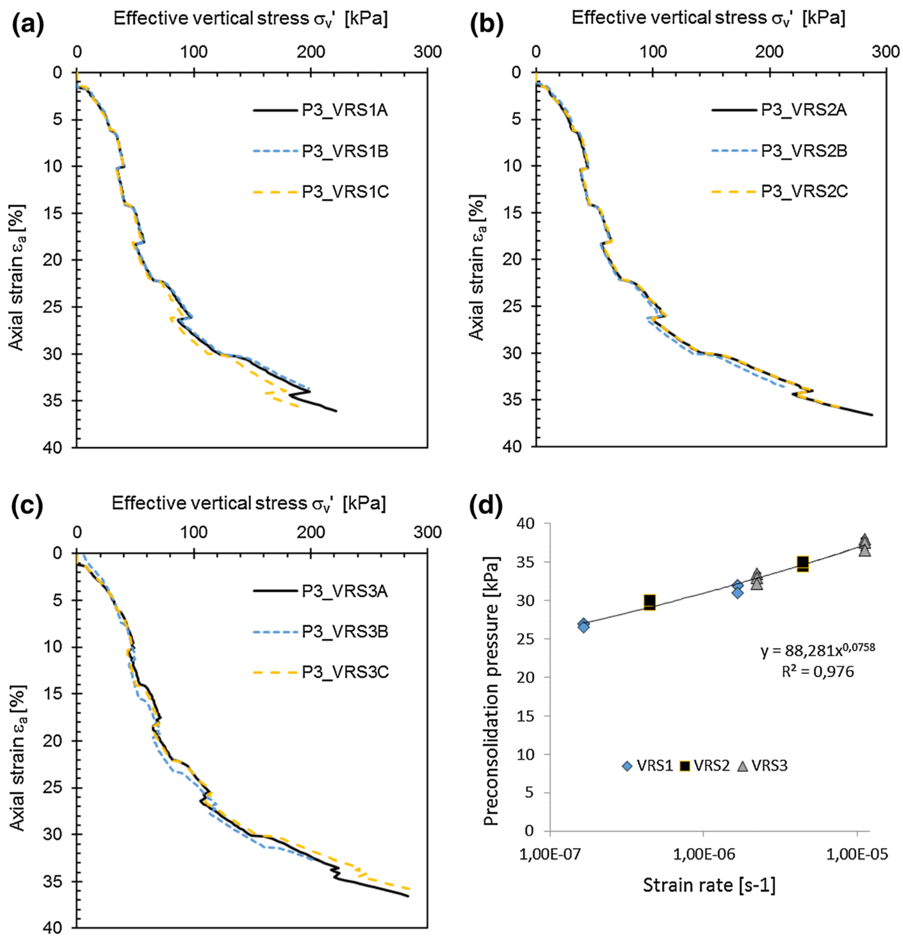

Fig. 7 VRS test from 3.3 to 3.7 m depth. **a** VRS1, **b** VRS2, **c** VRS3, **d** strain rate dependency of preconsolidation pressure from all VRS tests

Table 2 Sample data and obtained values for the rate parameter B for VRS test from 3.3 to 3.7 m depth. Clay content A represents A sample + half of B sample. Clay content C represents C sample + half of B sample

Test	VRS1				VRS2				VRS3			
	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*
A	3.45	97.0	70	0.074	3.54	89.8	65	0.067	3.63	93.7	66	0.078
B	3.42	97.0		0.074	3.51	94.8		0.068	3.60	95.9		0.079
C	3.38	99.8	70	0.068	3.48	93.0	67	0.068	3.57	89.2	64	0.078
Average		97.9		0.072		92.5		0.068		92.9		0.079

incrementally loaded oedometer test samples varied between the range w = 107–111%. The comparison of C_α values is shown in Fig. 8. As can be seen, the two different test types with nine VRS tests and 4 IL tests provided very similar C_α for the whole stress range.

6.2 Tests from Depth 5.4–5.7

The stress–strain curves for the nine VRS oedometer tests from samples at a depth interval of 5.4–5.7 are presented in Fig. 9. Again, the repeatability of the tests

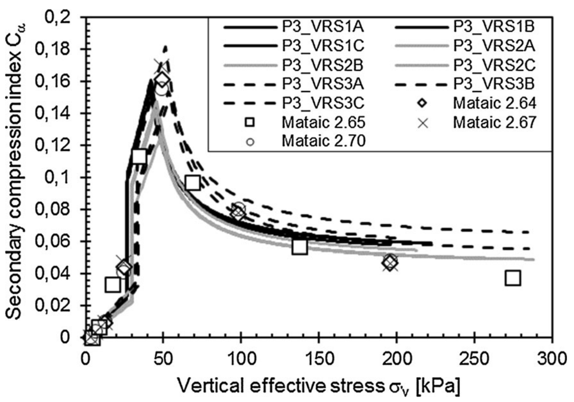

Fig. 8 Creep numbers from 9 VRS tests from depth 3.3–3.7 m compared to test results by Mataic (2016) from IL tests from the same clay layer but from a depth of 2.64–2.70

is good. The somewhat higher water content of samples P5_VRS1C and P5_VRS2C can be seen as higher compressibility.

The sample data as well as the evaluated strain rate parameters *B* from all the nine VRS tests are presented in Table 3. The rate dependency of the preconsolidation pressures from the nine tests is given in Fig. 9c). It is interesting to note that the rate parameter *B* evaluated from the rate dependency of the preconsolidation pressure from all the tests is equal to 0.082 and thus notably higher than the average from any of the test series. There is also much more variation in the results compared to the samples from depths around 3.5 m. This might, at least, partly be explained by differences in the samples. The content of fines smaller than

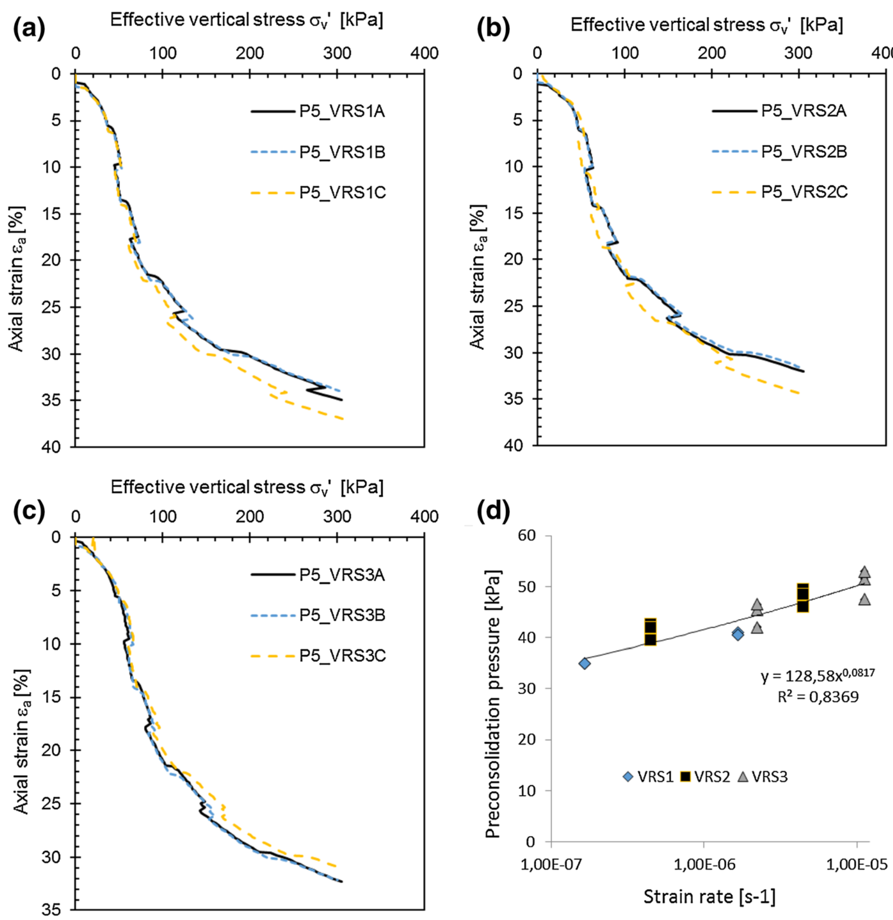

Fig. 9 VRS test from 5.4 to 5.7 m depth, **a** VRS1, **b** VRS2, **c** VRS3 and **d** strain rate dependency of preconsolidation pressure from all VRS tests

Table 3 Sample data and obtained values for the rate parameter B for VRS test from 5.4 to 5.7 m depth. Clay content A represents A sample + half of B sample. Clay content C represents C sample + half of B sample

Test	VRS1				VRS2				VRS3			
	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*
A	5.51	82.4	33	0.069	5.60	80.5	41	0.064	5.69	80.7	60	0.077
B	5.48	83.0		0.063	5.57	78.5		0.063	5.66	82.8		0.077
C	5.45	89.8	31	0.063	5.54	88.1	34	0.066	5.63	80.4	60	0.081
Average		85.1		0.065		82.4		0.064		81.3		0.078

0.002 mm increases from 31% for the topmost sample of VRS1 to 60% for the VRS3 series samples that are from the highest depth. The higher fine content might have increased structural bonding, resulting in higher preconsolidation pressures. It is interesting to note that if only results from VRS2 and VRS3 results from Fig. 9c) would be used, the rate parameter *B* would be equal to $B = 0.064$, i.e. close to the individual values.

The C_α values determined from the nine VRS oedometer tests are compared to values by Mataic (2016) from four IL oedometer tests, see Fig. 10. The IL oedometer test samples were from a depth of 5.0–5.5 and had a water content ranging between 64 and 121%. The variation in the water content is surprisingly high in the IL test series samples. The sample from depth 5.03 had an exceptionally high-water content of 121%, while for the others it was equal or less than 75%. With respect to the difference in water content, and the high variation of the water content in the IL oedometer tests, the results in Fig. 10 show good agreement.

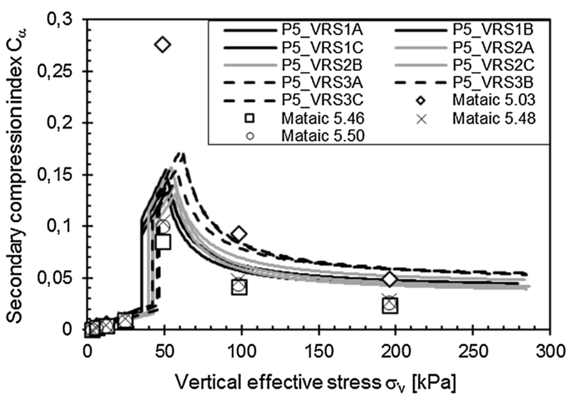

Fig. 10 Creep numbers from 9 VRS tests at 5.4–5.7 m depth compared to test results by Mataic (2016) from IL tests from the same clay layer but from a depth of 5.03–5.50

6.3 Tests from Depth 6.3–6.6

The stress–strain curves for the nine VRS oedometer tests from samples at depth intervals of 6.3–6.6 are presented in Fig. 11. Again, the repeatability of the tests is quite good, although the differences in the water content for VRS1 and VRS2 series can also be seen in the stress strain behaviour. The test P6_VRS1B ended due to technical problems.

The stress strain curves show a rather extreme behaviour after passing the preconsolidation pressure. The structure of the clay collapses and very large strains occur with very small increases in effective stress. The limit modulus M_L of the Sällfors model has an extremely low value between 50–100 kPa for most of the tests, emphasising the rather special behaviour of this clay. Yet, it is possible to determine the strain rate parameter *B* from these results also. The values of the strain rate parameter *B* from all the nine VRS tests and the corresponding sample data is presented in Table 4. The rate dependency of the preconsolidation pressures from the 9 tests is given in Fig. 11c. A similar but even more pronounced behaviour, as in the test from the depth of 5.4–5.7, can be observed. The rate parameter *B* evaluated from the rate dependency of the preconsolidation pressure from all the tests is now equal to 0.092 and thus considerably higher than in any of the test series. Interestingly, the rate dependency of the preconsolidation pressures from the different series VRS1, VRS2 and VRS3 seems to form a kind of stairs, i.e. the preconsolidation pressures are not at the same level. When the rate dependency of the preconsolidation pressures are evaluated independently from all of the series, the *B* values are $B = 0.072$, $B = 0.062$ and $B = 0.073$ for the series VRS1, VRS2 and VRS3 respectively. These values are again very close to the *B* values determined

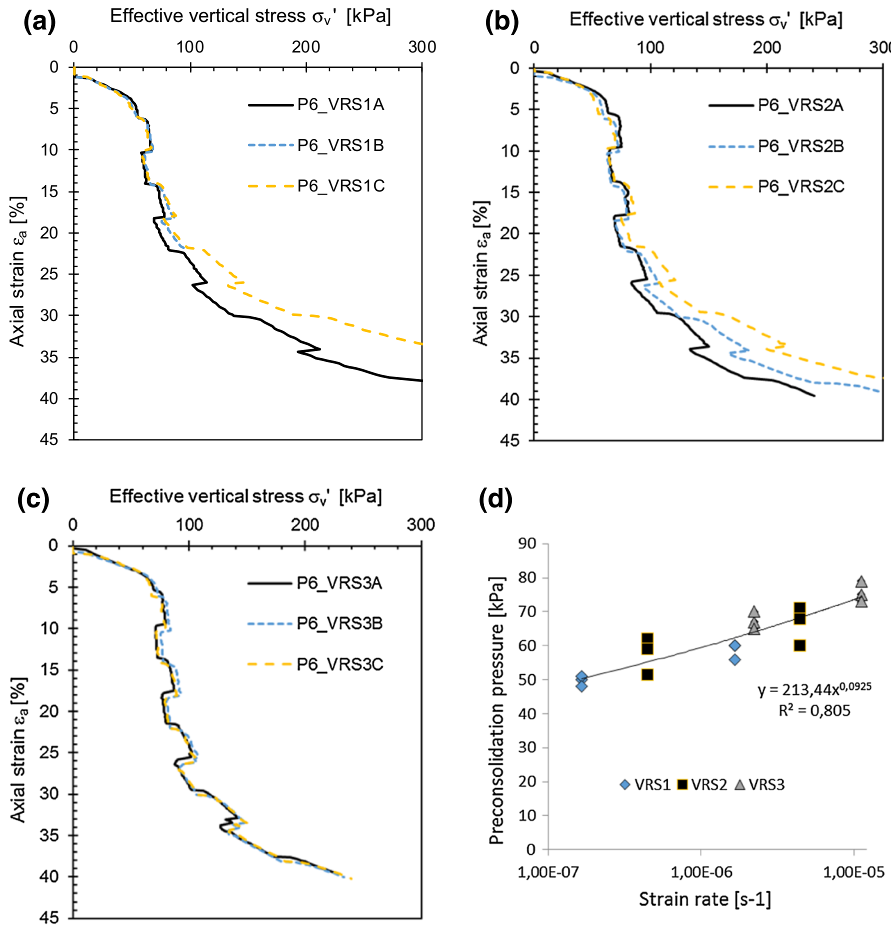

Fig. 11 VRS test from 6.3 to 6.6 m depth. **a** VRS1, **b** VRS2, **c** VRS3 and **d** strain rate dependency of preconsolidation pressure from all VRS tests

Table 4 Sample data and obtained values for the rate parameter B for VRS test from 6.2 to 6.5 m depth. Clay content A represents A sample + half of B sample. Clay content C represents C sample + half of B sample

Test	VRS1				VRS2				VRS3			
	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*	Depth (m)	*w* (%)	Clay (%)	*B*
A	6.28	101.6	*	0.079	6.40	134.0	85	0.059	6.49	134.4	92	0.065
B	6.25	82.5		0.071	6.37	105.5		0.062	6.46	132.4		0.075
C	6.31	86.7	*	0.067	6.34	99.7	80	0.066	6.43	129.5	94	0.071
Average		90.3		0.072		113.1		0.062		132.1		0.070

*Not available

from the individual tests. It is not known why the preconsolidation pressures seems to correspond to different levels for the different series. As can be seen from Table 4, the different series are from slightly different depths, with the average depth increasing 10 cm, going from test series VRS1 upwards. The clay content for VRS2 and VRS3 series samples is very high, being highest for VRS3 with the highest preconsolidation pressure level seen in Fig. 11d. There might thus well be a geological reason for this. Unfortunately, the clay content for VRS1 series, the mineralogical content, and the salinity of the samples are not known. It is, however, clear that the determination of rate parameter from the rate dependency of the preconsolidation pressure for all the tests will not provide the correct result.

The C_α values determined from the nine VRS oedometer tests are compared to values by Mataic (2016) from four IL oedometer tests, see Fig. 12. The IL oedometer test samples were from a depth of 6.24–7.76 and had a water content varying between 100 and 115%. The results from the two different test types again show a good agreement.

7 Discussion

As discussed earlier, the samples were taken with a 86 mm inner diameter NGI type piston sampler. Due to the limited diameter, oedometer samples were cut at successive depths from the centre part of the sampler cross-section. Although the oedometer samples are close to each other, there is some variability in both water and clay content. Generally, the three identical tests showed good repeatability, but the variability in water and clay content can be observed from the response. Higher water content yielded higher compressibility, and it seemed that higher clay content resulted in slightly higher preconsolidation pressure. The influence of clay content on the observed preconsolidation pressure can be due to higher structuration or less disturbance because of higher fine content. For two out of three depths, the interpretation of strain rate dependency, including all tests (d in Figs. 5, 7 and 9), showed a higher rate parameter B compared to the individual tests. This is due to

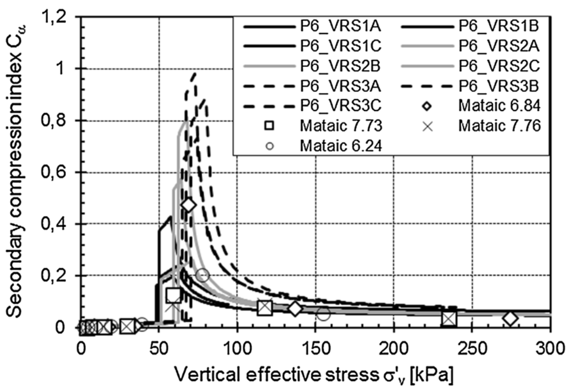

Fig. 12 Creep numbers from 9 VRS tests from 6.3 to 6.6 m depth compared to test results by Mataic (2016) from IL tests from the same clay layer but from a depth of 6.24–7.76

differences in the preconsolidation pressures between the test series, which are caused by differences in clay content. The best estimate for the rate parameter B is thus considered to be obtained from the individual tests.

The sensitivity of the investigated clay is rather high, especially for the samples at 6 m depth. Even though the structure of the clay seems to collapse after passing the preconsolidation pressure, the VRS tests yielded secondary compression index values equal to the IL tests, contradicting the observations by Claesson (2003). It is important to realize that this is because and incremental constrained modulus M is used which is true to the observed behaviour.

Although the results indicate that the C_α/C_C ratio is constant with respect to stress level, it is important to note that it is rate dependent. Field observations by Leroueil et al. (1988) indicate, quite clearly that, for very low strain rate values typical for field conditions, the C_α/C_C ratio is lower than what is observed in the laboratory tests. Watabe et al. (2012) provided further evidence that, for strain rates below 10^{-8} s^{-1} typically observed in the field, the C_α/C_C ratio decreases. This needs to be considered if one desires to reduce the preconsolidation pressure, determined from oedometer tests, to correspond to field strain rate values.

8 Conclusions

The main conclusions from this study on determination of creep properties for sensitive clays are as follows

- VRS oedometer test showed consistent behaviour and good repeatability.
- C_α values from the VRS tests agreed well with results from the independent IL tests.
- It is possible to describe the complex stress dependency of the creep parameters C_α and r_s with the aid of just one additional parameter to the primary deformation parameters, namely, the rate parameter $B = C_\alpha/C_C$.

As a consequence of the above, the VRS oedometer test can be used for the determination of C_α values for very soft and structured clays also. The benefits it offers compared to traditional IL test is a faster determination for a wide stress range and continuous values for the creep parameters.

The different tests series VRS1, VRS2 and VRS3, corresponding to different strain rates, seemed to provide consistent results. Test series VRS1 is rather slow, as it takes about 295 h to reach an axial compression of 30%. On the other hand, series VRS3, with only 24 h to reach 30%, seemed too fast, as the pore pressure ratio in the normally consolidated region reached maximum values of around u_{base}/σ_{total} = 25, 20 and 35% for samples from the three depths in increasing order. Although the results seemed to be in line with the results from the other test series, precaution is recommended if no previous experience exists from such high strain rates for the clay to be tested. A reasonable test procedure would thus be to use strain rates close to those of VRS2 series, which needed 110 h to reach 30% axial compression. For clays with lower clay content/higher permeability, higher strain rate values could well be equally applicable.

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