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New interpretation for consolidation modulus on chalk

Nouvelle interprétation du module de consolidation de la craie

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ABSTRACT: The North Sea basin is an area where chalk is frequently present near the surface. Therefore, also in Denmark, it happens that many heavy structures are built on top of chalk. The design of such foundations requires, among others, the consolidation modulus determined from oedometer tests. This paper presents results from oedometer tests on chalk from Rørdal, Denmark. Oedometer results are analysed according to several strain separation methods, to filter the consolidation strains from the creep strains. Traditionally, the consolidation strains are filtered between primary consolidation strains and creep strains by using well known methods (i.e. Taylor and Brinch –Hansen methods). However, by analysing the tests it appears that these methods may not be suitable for describing the behaviour of chalk. This inaccuracy in the interpretation is caused by both the fabric crushing at each load step and very small consolidation strains detected, even on a long term behaviour. To account for this, the paper presents a method that takes into consideration the fabric crushing at each load step. As an effect of this new interpretation, there is a more precise consolidation modulus.

RÉSUMÉ: Bassin de la Mer du Nord, la craie est souvent présente en surface. Au Danemark, ce type de sol est souvent rencontrer sur des projects ou les charges au sol sont importantes. La conception de telles fondations requière, entre autres, le module de consolidation déterminé à partir de tests oedométriques. Cet article présente les résultats de tests oedométriques effectués sur de la craie de Rørdal (Danemark).Les résultats de l'oedomètre sont ensuite analysés selon plusieurs méthodes, afin de séparer les contraintes de consolidation des contraintes de fluage. Traditionnellement, des méthodes bien établies (i.e. Taylor and Brinch –Hansen metods) sont utilisées pour séparer les contraintes de consolidation primaire des contraintes de fluage. Cependant, l'analyse de ces tests révele que ces méthodes ne sont peut-être pas adaptées pour décrire le comportement de la craie. Cela peut être expliqué par l'écrasement de la structure à chaque étape de chargement ainsi que par de très petites contraintes de consolidation détectées même sur un comportement à long terme. Pour en tenir compte, cet article présente une méthode tenant compte de l'écrasement de la structure à chaque étape de chargement. En conséquence, on pent obtenir un module de consolidation plus précis.

Keywords: Chalk; oedometer test; crushing; creep; consolidation modulus.

1 INTRODUCTION

Chalk is a common material nearby Aalborg and in general in the North Sea basin (Ziegler, 1990). In this area chalk is found near the surface and it can directly affect the performance of structures built on the top of it. Despite its abundance, Rørdal chalk has not been frequently investigated in the literature. And since the chalk presents a wide variety of physical and chemical properties, a general description of the material and an assumption of its mechanical characteristics *a priori* are not realistic.

Moreover, chalk has been approached differently in the past literature. Some authors refer to it like a fine grained sedimentary rock (Korsnes et al., 2008; Hjuler and Fabricius, 2009), instead, others treat chalk like a soil (Kågeson-Loe et al., 1993; Leth et al., 2016). Its mechanical properties are examined by uniaxial compression tests (Palchik and Hatzor, 2004), brazilian test ((Korsnes et al., 2008), (Risnes and Flaageng, 1999)), triaxial (Kågeson-Loe et al., 1993) and oedometer tests (Leth et al., 2016). The work presented in this paper deals specifically with chalk found in the Rørdal quarry, where it is possible to find chalk from the surface level to variable depth. The tested material was deposited during the Late Cretaceous in the Maastrichtian Age.

The present work provides an insight on the time – dependent behaviour of Rørdal chalk. To do so, chalk performance is investigated in incremental load oedometer tests. The axial strain – time curve is analysed, finding out an initial sudden strain followed by smaller consolidation and creep strains. The relationships between these three contributions and the stress are quantified for the tests, and a strain separation method is applied. Considering the results found by previous works on creep in chalk ((Andersen et al., 1992), (Gennaro et al., 2003)), load steps one week long or more are expected to give an appreciable axial strain due to creep.

2 METHOD

At the beginning of the present paragraph, the origin and the properties of the chalk are discussed. Later, the different equipment adopted and the experimental set-up are described.

2.1 Material

The chalk tested comes from the Rørdal quarry near Aalborg, in Denmark. The analysed material was excavated from a depth of about 8 m (see Figure 1). The night before the blocks were collected from the ground, the excavator operated on the surface. By doing so, the material was not exposed to the sun. Twelve blocks were collected and sealed in plastic bags. The chalk was stored in a refrigerator with a constant temperature of 7°C until the samples preparation phase.

Figure 1. Chalk surface excavated at the quarry

2.2 Chalk properties

Some classification tests were performed to determine various parameters (Nielsen et al., 2018). The results from these tests are listed in Table 1. These properties classify the chalk tested as a very soft chalk (VS) according to the IDD-NMC diagram. On chalk from the same area previous studies determined a calcium content* equal to 93.8% (Hjuler and Fabricius, 2009) and a consistent amount of coccoliths and an high porosity (Tucker et al., 1990; Hjuler and Fabricius, 2009).

*Table 1. Chalk properties. *The calcium content of 93.8% was reported by* (Hjuler and Fabricius, 2009)

Property	
Water content, w (%)	28
Total density, ρ_t (Mg/m^3)	2.11
Dry density, ρ_d (Mg/m^3)	1.65
Specific gravity, G_s (-)	2.7
Void ratio, e (-)	0.84
Porosity, n (%)	46
Calcium content* (%)	93.8%

2.3 Experimental program

The experimental program includes nine oedometer tests and, for each of them, the sample dimensions are given in Table 2. Among them, five tests were performed in a GDS® apparatus with fixed ring. The other four were run in the Aalborg University oedometer apparatus, using hanging weight and floating ring. The samples tested in the AAU apparatus present two different sizes: two samples have height (H) by diameter (D) equal to 35×35mm, the other two have size H×D=20×35mm. All the samples tested in the GDS® oedometer have the same size: D equal to 70mm and H equal to 35mm.
The samples are named as XXYY, where XX refers to the block sample name, and YY refers to the consecutive numbering of tests on the same block. Table 2 sums up the notation assigned to each sample.

Table 2. Sample notation

Load	Test	H×D	Block
Hanging weight – AAU oedometer	0903	20×35	09
	1001	35×35	10
	1103	20×35	11
	1201	35×35	12
GDS® load control	0103	35×70	01
	0901	35×70	09
	0902	35×70	09
	1101	35×70	11
	1102	35×70	11

The chalk proved to be a very challenging and time consuming material to work on. The sample preparation turned out to be extremely demanding. More details about the sample preparation preliminary to this paper are found in (Nielsen et al., 2019). The nine samples come from five (out of the twelve collected from the chalk pit) original blocks. Since the chalk blocks are excavated and later picked up in the quarry, the vertical and horizontal direction of the blocks are unknown. Starting from the initial block, the final sample was prepared through a drilling phase and pushed out from the drilling cylinder. In this way all the samples were fit into the oedometer ring and finally levelled to the final desired height by hand. In order to reach the full consolidation, each load step lasted 168 hours (one week); only exception was the last step in each GDS® oedometer, that load was left running for one month.

2.3.1 *Aalborg University oedometer*

The AAU oedometer apparatus was designing by Moust Jacobsen in 1970 (Jacobsen, 1970). It aims to reduce inaccuracies due to the deformation of the traditional apparatus itself. This apparatus implies a cell that is similar to the one in the normal oedometer, but the hanging weight is applied through a ball connected to the top cap and the ring is a so-called floating ring. Figure 2 illustrates a section of the AAU oedometer.

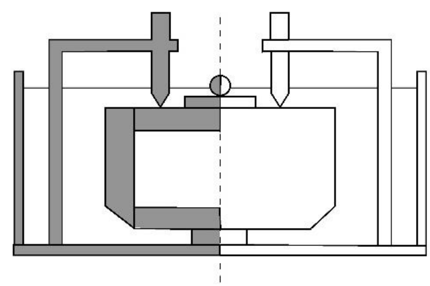

Figure 2. AAU oedometer (not in scale)

Each load step lasted 168 hours, and it was possible to reach a maximum stress equal to 28.5 MPa. In Table 3 the load steps followed in the hanging weight oedometer are listed.

Table 3. Load steps in AAU oedometer

Test	Load steps [kPa]
0903, 1103	122.31; 254.82; 509.64; 1019.3; 2038.6; 3567.5; 7135; 14270; 28540; 7135; 2038.6; 509.64; 122.31; 509.64; 2038.6; 7135; 28540; 0
1001, 1201	30.58; 61.16; 122.31; 254.82; 509.64; 1019.3; 2038.6; 3567.5; 7135; 14270; 28540; 7135; 2038.6; 509.64; 122.31; 509.64; 2038.6; 7135; 28540; 0

2.3.2 *GDS® oedometer*

The GDS® oedometer system adopted substitutes the hanging weight by applying the load with a

motor in the stand-alone unit. External transducers register the deformation and the maximum load applicable is 10kN. The pressure applied to the chalk is different between AAU oedometer and GDS® oedometer because of the bigger sample size adopted in the GDS® oedometers. So, in these apparatus, it was possible to reach a maximum stress equal to 2.6 MPa. Each load step lasted 168 hours except the last one, during which the load was left for an entire month.
In Table 4 the load steps followed in the GDS® oedometer are listed.

Table 4. Load steps in GDS® oedometer

Test	Load steps [kPa]
0103	31; 64; 128; 255; 510; 893; 1786; 2598; 1786; 510; 128; 31; 128; 510; 1786; 2598, 0.
0901 0902	31; 64; 128; 255; 510; 893; 1786; 2598; 1786; 510; 128; 31; 128; 510; 1500.
1101	31; 64; 128; 255; 510; 893; 1786; 2598; 1786; 510; 128; 31, 128; 2598, 0.
1102	31; 64; 128; 255; 510; 893; 1786; 2598; 1786.

2.4 ANACONDA: separation of strain

During the interpretation phase, each load step is analysed and the creep strains are separated from the consolidation strains. To do so, the ANACONDA method - ANAlysis of CONsolidation test DAta - is applied (Jacobsen, 1992a). This method considers the primary and the secondary consolidation processes being two processes running simultaneously.

In Bjerrum settlement analysis (Bjerrum, 1967), studying the consolidation isochrones in a log*(t)* - ε, a strain value can be reached by primary consolidation or creep. An isochrones, at time $t=t_A$, quantifies the time past in order to get a specific strain value (see Figure 3). ANACONDA assumes that the primary consolidation is over at the time $t= t_A$ and, from that moment, the creep is the major contribute to the strain. Among the total strains ε_{tot} (%), the difference between primary consolidation strain ε_c (%) and creep strain $\Delta\varepsilon_{\alpha c}$ (%) is seen in the ε–log*(t)* graph, where the creep strains get into a straight line (see Figure 4).

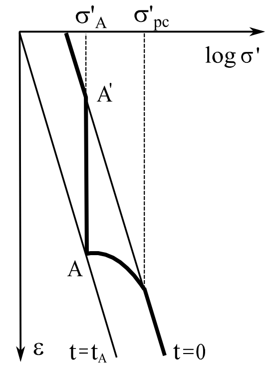

Figure 3: instant compression curve t=0 and secondary compression isochrones (Jacobsen, 1992b)

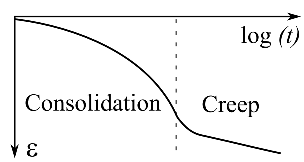

Figure 4: consolidation and creep (Jacobsen, 1992a)

It is possible to determine t_A from the equation:

$$\Delta\varepsilon_{\alpha c} = C_{\alpha\varepsilon} \log\left(1 + \frac{t}{t_A}\right) \quad (1)$$

Where $C_{\alpha\varepsilon}$ is the secondary compression index. The proper t_A transforms the $\Delta\varepsilon_{\alpha c}$ – log $(1+t/t_A)$ curve into a straight line, where $C_{\alpha\varepsilon}$ is the slope (see Figure 5).

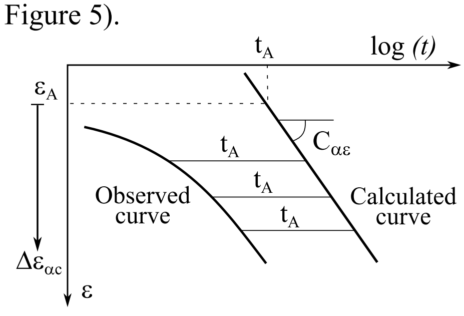

Figure 5: observed curve and the delay of time

Once the $\Delta\varepsilon_{\alpha c}$ is found, in order to get the ε_c value, it is possible using the relationship:

$$\varepsilon_c = \varepsilon_{tot} - \Delta\varepsilon_{\alpha c} \quad (2)$$

When the creep becomes the major contribute, if the ε_c – log(*t*) line is horizontal, the $\Delta\varepsilon_{\alpha c}$ calculated is right.

3 RESULTS

Despite the samples came from the same quarry (in some cases even from the same block) and the adoption of a common preparation technique, the consolidation curves obtained are not easy to compare with each other and present a remarkable variability in the maximum deformation reached. Main focus is on tests 1201, 1001, 0903 and 1103.

3.1 Before separation of strain

3.1.1 Analysis of a single load step

Even if the final consolidation curve is unique for each test in terms of shape and final strains reached, there are common features between the different ε [%] - log*(t)* [min] graphs plotted for each load step. In fact, it can be seen a significant immediate deformation, happening in the first few seconds, followed by a very slow and often lower deformation rate (see Figure 6). Applying a separation of strains with the well-known methods (i.e. Brinch-Hansen or Taylor methods) does not suit the chalk, because these methods constructions are based on soils for which the ε - log*(t)* graphs have a different time response.

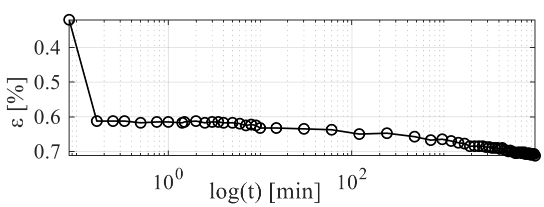

Figure 6: test 0903, step 3: 509 kPa are applied

3.1.2 Stress – strain behaviour

The nine consolidation curves are displayed in the ε - logσ graph in Figure 8where it is not applied the strain separation between primary consolidation and creep.

It can be noted a quite consistent variability between the final strains reached in the two groups of results (hanging weight and GDS® oedometers). The tests show a steady compressive behaviour. Among the hanging weight oedometer results the inclination of the unloading segments is similar. Noticeable common feature is the remarkable preconsolidation stress detected. It is not to discard the possibility that additional load points could change the curve and return higher values of preconsolidation stress. With the applied load steps, the preconsolidation stress in test 1201, test 0903 and test 1103 is within the interval of 5000 – 7000 kPa; only test 1001 seems to give back a greater value. On the other hand, in the GDS® oedometers, the consolidation curve is very far from detecting the virgin compression because of the lower pressure applied. And due to this reason, the unloading and reloading segment is almost horizontal in these tests (see Figure 7).

If the oedometer tests on chalk were run only under low stress levels (like the ones applied in the GDS® oedometer), they would give an unrealistic low estimation of preconsolidation stress, and unrealistic high consolidation modulus and compression index. Instead, high applied stresses were fundamental to detect the virgin compression curve and the deformation properties. For this reason, in the next paragraph only tests presenting the most matured virgin compression curves are analysed. The separation of strains is so applied on tests 1210, 1001, 0903 and 1103.

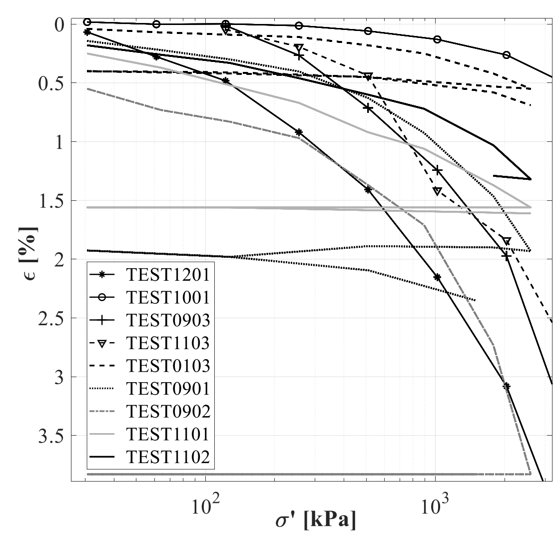

Figure 7: zoom on not filtered GDS® oedometer results

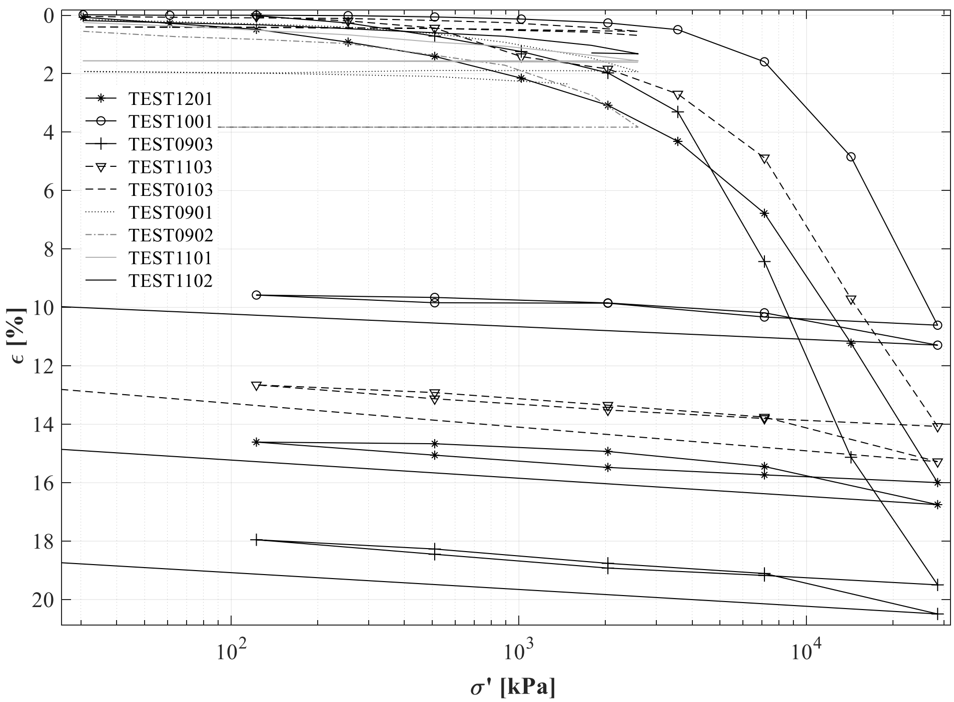

Figure 8: nine oedometer results with no strain separation

3.2 Separation of strains: crushing and ANACONDA

3.2.1 Interpretation of a load step

In paragraph 3.1.1 one load step is taken as example, showing a sudden deformation, followed by consolidation strain ε_{cons} and finally creep strain ε_{creep} (see Figure 9). The initial deformation is called $\varepsilon_{crushing}$, because it is probably due to grain breakdown. To detect these three separate phases among the total strain, the load step needs to be as long as possible, otherwise the creep stage cannot be reached.

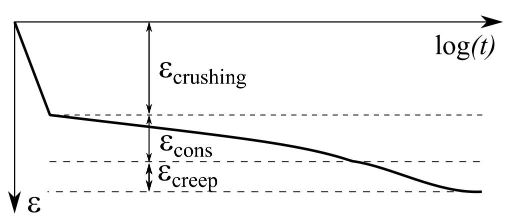

Figure 9: Interpretation of the single load step

As introduced in paragraph 2.4, ANACONDA method separates primary consolidation and creep. As an example, Figure 10 illustrates how the creep (in yellow) becomes the main contribution to the deformation as soon as the consolidation line (blue) becomes horizontal. Moreover, it can be noted an initial relative high strain: this is the so-called crushing strain in Figure 9.

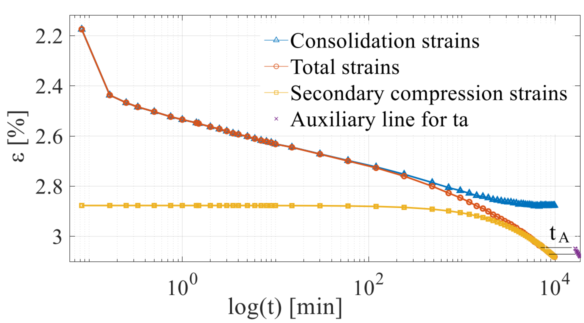

Figure 10: ANACONDA applied to Test 1201 step 7

3.2.2 New interpretation of stress – strain behaviour with ANACONDA

By removing $\varepsilon_{crushing}$ and ε_{creep} from each load step, new consolidation curves are calculated considering only the primary consolidation strains contribution. Figure 11 quantifies the crushing in the four tests analysed. For example, test 1201 shows $\varepsilon_{crushing} = 5\%$, that is equal to one third of the detected total strains.

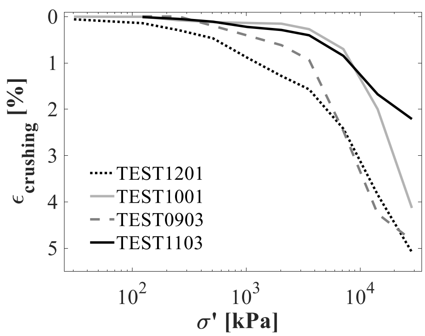

Figure 11: cumulative initial crushing

In Figure 12 the virgin compression lines are displayed without any filter (as previously done in Figure 8) and with no $\varepsilon_{crushing}$ and ε_{creep}. It can be seen again that the contribution of these two strains is not negligible; for example, for test 1201 $\varepsilon_{crushing}$ and ε_{creep} are equal to 6%, while the total strains are 16%.

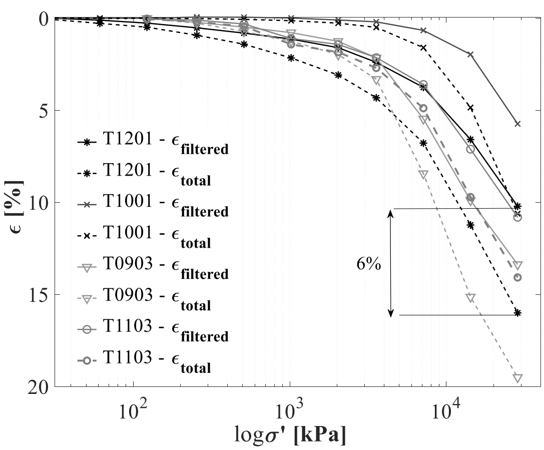

Figure 12: strains before filtering (dotted lines) and after filtering $\varepsilon_{crushing}$ and ε_{creep}

4 DISCUSSION

Remarkable is the variability among different consolidation curves. There is no consistency in the total strains and in preconsolidation stresses from different tests. A main role is played by the possibility to apply higher stress and so reach the virgin compression curve. Despite these discrepancies it is possible to distinguish three separate contributions among the strains: crushing, consolidation strains and final creep. The initial strain can be interpreted as grain crushing or progressive pore breakdown or destruction of fabric (Kågeson-Loe et al., 1993).
The initial strain is not believed to be an adjustment to the ring, as the samples, after the test, still had areas where they were not adapted to the ring completely. The crushing is useful to predict settlements during the construction phase of a structure, while it can be neglected on a long term structure behaviour.

Parameter influenced by this new interpretation is the consolidation modulus *M* (MPa). The consolidation modulus is a stiffness parameter given by:

$$M = \frac{\Delta\sigma}{\Delta\varepsilon_{cons}} \qquad (3)$$

where $\Delta\sigma$ and $\Delta\varepsilon_{cons}$ are the increments of stress and strains. The new interpretation returns a higher *M* (but similar in trend) and so a stiffer soil. For example, the percent error (averaged among all the stress values) between *M* without any filter and the *M* given by the new interpretation is equal to 32% for test 0903. Figure 13 shows the new curves for *M* in tests 1201, 0903 and 1103.

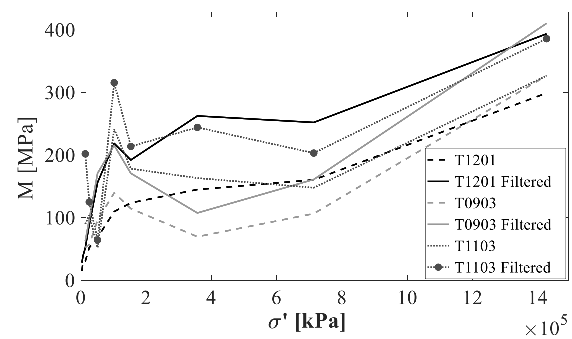

Figure 13: Modulus M before and after filtering

5 CONCLUSIONS

In this paper a new interpretation method for oedometer test on chalk is presented. The chalk tested, because of its softness, can be considered a material in between a rock and a soil. Moreover, each load step shows three separate strain phases. So, it is clear how the traditional methods employed to separate primary consolidation and creep strains are not suitable in this case.

The new interpretation method starts with detecting the three strains phases and filtering the consolidation strains from the rest. The two contributions to be taken out are the initial strain due to grain crushing and the final creep. The remaining "real" consolidation strains give more precise preconsolidation stress and consolidation modulus. The new modulus is higher than the one got without filtering crushing and creep.

The new interpretation method requires to perform oedometer tests with long time load steps and to apply stresses large enough in order to reach the virgin compression curve.

6 ACKNOWLEDGEMENT

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