Positive influence of unloading after Ménard Vacuum Consolidation on long-term creep behavior of soft soils

Influence du déchargement avec le procédé "Ménard Vacuum Consolidation" sur le comportement de fluage à long termes des sols meubles

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ABSTRACT: Preloading is commonly used in to improve the mechanical properties of soft soils. The aim of preloading is to allow settlement to take place prior to construction and minimise secondary compression after construction. The increase in effective stress required for preloading can be induced either by applying a temporary surcharge, usually in the form of an embankment, or by placing the soil mass under vacuum. In this study, the influence of preloading and unloading on secondary compression behavior is demonstrated by one-dimensional compression tests of North German clay and peat. The secondary compression of soils can be significantly reduced by overconsolidation. However, during the recompression phase of an overconsolidated soil, the coefficient of secondary compression $C_{\alpha r}$ does not remain constant as during virgin compression, but instead increases with time. This behavior is due to the fact that secondary compression follows the C_α/C_c law of compressibility and that C_{cr} increases with effective vertical stress during recompression. If only minor unloading occurs, the preloading stress can be exceeded by the increase in equivalent stress associated with creep. If this is the case, a normally consolidated soil will behave under virgin compression conditions. In order to estimate the coefficient $C_{\alpha r}$, the relationship between the quotient $C_{\alpha r}/C_\alpha$ and the recently proposed recompression ratio, or RCR, is explored. Furthermore, the influence of the degree of consolidation in preloading on primary and secondary consolidation during recompression behavior is demonstrated.

RÉSUMÉ: Le préchargement est un procédé largement répandu pour l'amélioration des caractéristiques mécaniques des sols mous. Outre l'anticipation du tassement primaire, le but du préchargement est de réduire le tassement secondaire après construction. La contrainte effective supplémentaire peut provenir du poids d'un remblai temporaire, mais aussi par l'application d'une dépression atmosphérique. Basé sur des tests de compression unidimensionnels sur de l'argile et de la tourbe du nord de l'Allemagne, l'influence du pré- et déchargement sur le tassement secondaire a été prouvée. Ce tassement secondaire des sols peut être réduit significativement par une surconsolidation. Mais à l'opposé de la compression dite « vierge », lors d'une post surcharge, l'indice de consolidation secondaire $C_{\alpha r}$ augmente avec le temps. Ce comportement s'observe car la consolidation secondaire qui entre en jeu après la suppression de la surcharge suit la loi de compressibilité C_α/C_c de Mesri-Godlewski (1977) est constant, et lors de la reconsolidation, C_{cr} augmente sous l'effet d'une contrainte vertical effective. Si le déchargement est trop faible, la pression de préconsolidation est dépassée par le fluage et la partie de tassement secondaire est du même ordre que celle de la partie vierge de compression. Un écart suffisant entre le déchargement et un faible rechargement est alors nécessaire pour réduire le tassement issu de la reconsolidation secondaire. Afin d'estimer le coefficient $C_{\alpha r}$, on se propose d'étudier la corrélation entre le rapport $C_{\alpha r}/C_\alpha$ avec un indice de recompression nommé RCR. L'influence du degré de consolidation lors du préchargement sur le comportement de recompression primaire et secondaire a de plus été démontrée.

KEYWORDS: creep, secondary compression, preloading, overconsolidation, vacuum-consolidation, recompression

1 INTRODUCTION

Soft soils with high organic content, such as North German clay and peat, pose a challenge for the construction industry due to their high compressibility and long-term creep behavior. In order to prevent unacceptably large consolidation settlements from occurring during and after construction, soft soils are often preloaded to allow settlement to take place prior to construction. This is usually done by applying a temporary surcharge, in the form of a sand or gravel embankment construction, in combination with vertical drains. Ménard Vacuum Consolidation is an alternative method of preloading, in which total stress is constant and pore water pressure is reduced under vacuum in order to increase effective stress (Cognon 1991). Before reloading, the system is turned off and, in contrast to the standard preloading procedure, significant unloading occurs before the ground is reloaded.

In order to calculate the duration and amount of preloading required to achieve a certain amount of residual settlement, it is necessary to know the creep behavior, or secondary compression, of a soil. Secondary compression behavior during intial compression can be described by the coefficient of secondary compression C_α. However, preloading and subsequent unloading has a significant effect on secondary compression, requiring initial loading and reloading to be evaluated separately.

The aim of this investigation is to determine the secondary compression behavior of soft organic soils after preloading through oedometer testing, in order to evaluate the main effects of preloading methods and prove the effectiveness of these methods.

2 SECONDARY COMPRESSION BEHAVIOR OF SOFT SOILS

The secondary consolidation of a soft soil is characterised by its deformation after the reduction in excess pore water pressure (primary consolidation) has taken place. The parameters of secondary compression are determined graphically by plotting the change in the void ratio over time on a logarithmic scale.

Assuming a typical S-shaped *e*-log *t* curve, the change from primary consolidation to secondary consolidation occurs at the end-of-primary (EOP) consolidation (Fig. 1).

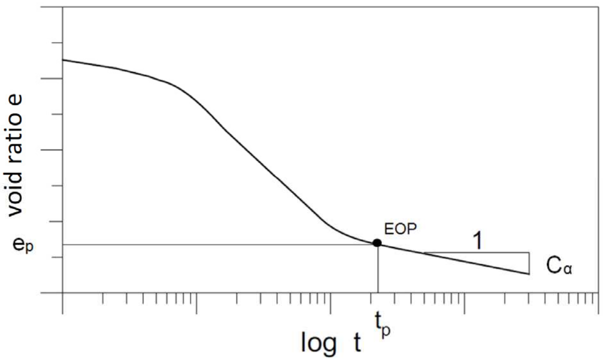

Fig. 1. Typical *e*-log *t* curve for a soft soil

After time t_p, the curve straightens and the change in void ratio Δe^v occurs as a result of secondary consolidation. It follows that the coefficient of secondary compression can be written as:

$$C_\alpha = \Delta e^v / \Delta \log t \quad (1)$$

Under virgin compression conditions the relationship between the void ratio and logarithm of time is roughly linear, so that it can be assumed that C_α = *const* for a particular load. Numerous studies have shown that the coefficient of secondary compression C_α and the compression index C_c (= $\Delta e^v / \Delta \log \sigma'$) are independent of stress in the range of realistic stress conditions during virgin compression (Krieg 2000). The quotient C_α/C_c always remains constant and is therefore independent of void ratio and stress (Mesri and Godlewski 1977). C_α/C_c is thus a soil mechanical parameter and depending on the soil type ranges from 0.01 to 0.07 (Mesri 2001). The value of C_α/C_c together with the EOP *e*-log σ'_v curve completely defines the secondary compression behavior of any one soil (Mesri and Castro 1987).

3 RESULTS

3 .1 *Materials and methods*

Conventional incremental loading oedometer tests were carried out on undisturbed samples of organic clay and peat from North Germany. The samples were prepared by trimming the soil to fit into the consolidation oedometer rings, initially 8 cm in diameter and 1,5 cm in height. The rings were lubricated with silicon grease to reduce friction and filter papers were placed on the top and bottom of the samples. In all cases, drainage was permitted at both sides of the samples. The temperature of the constant temperature water-bath was maintained at 18 ± 2°C. All samples were obtained from 1 ~ 2 m below the ground surface, using a thin-walled fixed-piston sampler in order to reduce disturbance as best as possible.

In this study we present the results of compression tests carried out on organic clay with soil mechanical parameters as shown in Table 1.

Table 1. Soil properties and mechanical parameters of investigated clay

soil	e_0	w_0 [%]	LOI [%]	C_α	C_α/C_c
Organic Clay	3.6	140	12	0.08	0.056

3.2 *Secondary Compression behavior during reloading*

During the recompression phase of an overconsolidated soil, the coefficient of secondary compression is not constant like during virgin compression, but instead it is dependent on stress and time. $C_{\alpha r}$ is a useful designation to describe creep behavior during reloading (Tinat and Rosenberg 2016). Plotted against the logarithm of time, the rate of secondary compression increases continually. This property can be related back to the increasing of equivalent stress σ'_e, with a similarly nonlinear relationship existing between void ratio and logarithm of effective stress during reloading (Fig. 2). The law of compressibility by Mesri and Godlewski 1977 also holds for the recompression phase, with $C_\alpha/C_c = C_{\alpha r}/C_{cr}$ = *const*. The effect of preloading on C_α is therefore proportional to its effect on the compression index C_c.

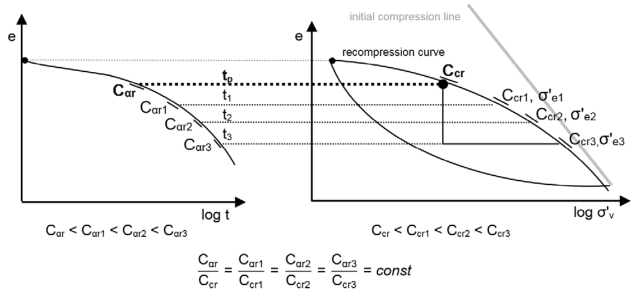

Fig. 2. Corresponding values of increasing $C_{\alpha r}$ and C_{cr} during reloading (Tinat and Rosenberg 2016)

Contrary to the common assumption for normally consolidated soils, the isochrones of the *e*-log σ'_v curves are neither linear nor parallel to one another during reloading (Fig. 3). This often overlooked property can be related back to the dependence of $C_{\alpha r}$ on stress and time. Through numerous oedometer tests, isochrones were developed for the clay. $C_{\alpha r}$ increases by factor 2.5 until 1000tp.

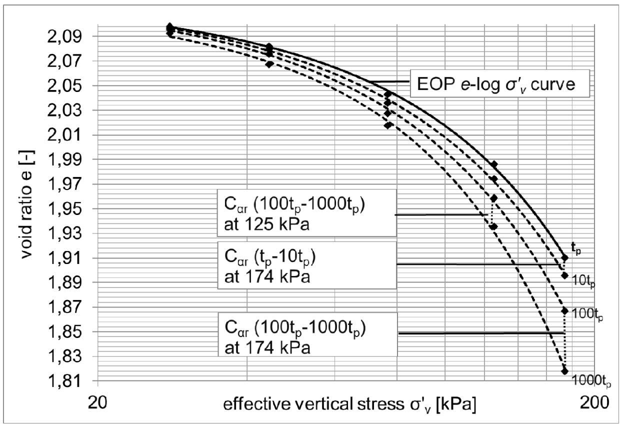

Fig. 3. Isochrones of *e*-log σ'_v curves in the recompression range of an overconsolidated clay (Tinat and Rosenberg 2016)

It was also shown that the preloading stress can be exceeded through creep and the associated increase in equivalent stress alone. After this happens, a normally consolidated soil will behave under virgin compression conditions, with the coefficient of secondary compression $C_{\alpha r} \rightarrow C_\alpha$ = const (Tinat and Rosenberg 2016).

3.3 *Influence of the degree of consolidation on unloading and reloading behavior*

The influence of the degree of consolidation on unloading and reloading behavior of clay at constant effective preloading stress was investigated in three of the oedometer tests. To this end, the last load increment of preloading for these tests was carried out such that the equivalent effective preloading stress σ'_{ep} was kept constant at 120 kPa at the time of unloading, with different values for the total stress σ.

In test 3 the total vertical stress of σ_v = 94 kPa was applied. After primary consolidation, the secondary compression was maintained for 6 days (t/t_p = 72). Within this period the equivalent effective stress σ'_e increased to 120 kPa due to the creep-aging effect. At the time of unloading the sample was overconsolidated through the process of secondary consolidation ($\sigma'_{ep} > \sigma'_v$).

In test 4 the total and effective vertical stress at the time of unloading were approximately equal. After applying the load the sample was allowed to fully undergo primary consolidation (U_p = 1).

In test 5 a total vertical stress of σ = 155 kPa was applied and the primary consolidation phase stopped after the effective stress σ'_e of 120 kPa was reached. The excess pore water pressure was not yet fully drained (U_p = 0,7).

In all tests swelling behavior was observed after a reduction in total stress, with a resulting heave and increase in void ratio. Time dependent swelling deformation was observed, with no final deformation recorded. The time dependent swelling is due to viscous soil behavior and comparable to secondary compression under an increase in stress (Krieg 2000). The magnitude of elastic heave is highly dependent of the degree of consolidation of the preloading. After a secondary consolidation phase the soil became significantly stiffer and showed a low swelling capacity (Fig. 4).

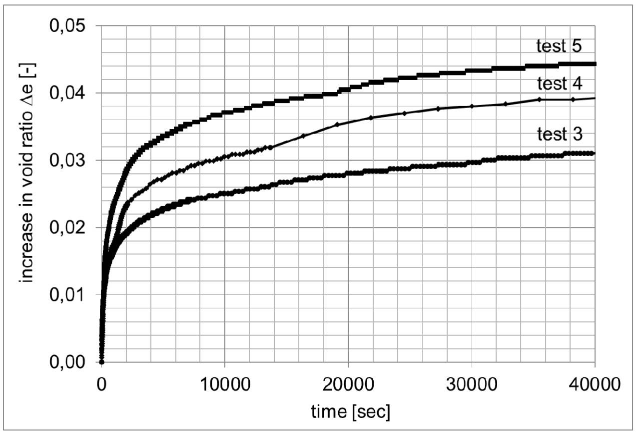

Fig. 4. *e*-log *t* curves of one unloading increment

The largest swelling capacity occurred with a degree of consolidation < 1 during preloading. The incomplete primary consolidation and resulting excess pore water pressure caused a greater magnitude of rebound. The higher amount of swelling compared to the other tests was observed in all stages of unloading. The influence of preloading was not limited to the first unloading increment, but continued to have an effect even after the excess pore water was drained. Clearly the cohesive forces between soil particles are dependent on the degree of consolidation and type of deformation (primary or secondary consolidation).

The conditions of consolidation of preloading affects both the swelling and recompression behavior during reloading. This is due to the dependence of reconsolidation on how much swelling occurred previously. Pronounced unloading causes heaves, which in turn results in greater deformation during reloading. Swelling deformation thus directly influences settlement behavior and stiffness during reloading. Figure 5 shows the unloading and reloading paths of the three tests for the abovementioned degrees of consolidation.

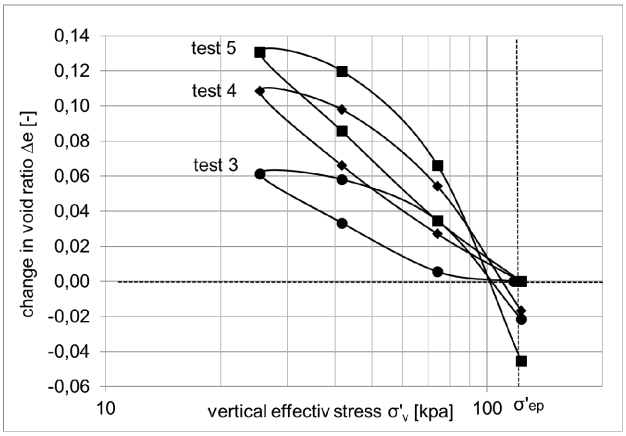

Fig. 5. *e*-log σ'_v curves of unloading and reloading in test 3-5

The different *e*-log σ'_v curves highlight the influence of the degree of consolidation of preloading on the swelling and recompression behavior of cohesive soils. If a creep phase occurs during preloading, elastic rebound and the associated deformation will be significantly reduced when the soil is reloaded.

A soil that is not yet fully consolidated at the time of unloading, with U_p < 1, will exhibit more elastic rebound and associated deformation than a fully consolidated soil with U_p = 1.

4 ESTIMATION OF LONG-TERM CREEP BEHAVIOR

In all tests carried out on clay and peat, a linear correlation between the quotient $C_{\alpha r}/C_\alpha$, or C_{cr}/C_c, and the newly developed recompression ratio RCR (Tinat and Rosenberg 2016) was proven semiempirically. A correlation with the oversonsolidation ratio OCR does not exist. The RCR is defined as follows (Fig. 6):

$$RCR = \frac{\sigma'_1 - \sigma'_0}{\sigma'_{ep} - \sigma'_0} = \frac{\Delta\sigma'_{recompression}}{\Delta\sigma'_{rebound}} \leq 1 \qquad (2)$$

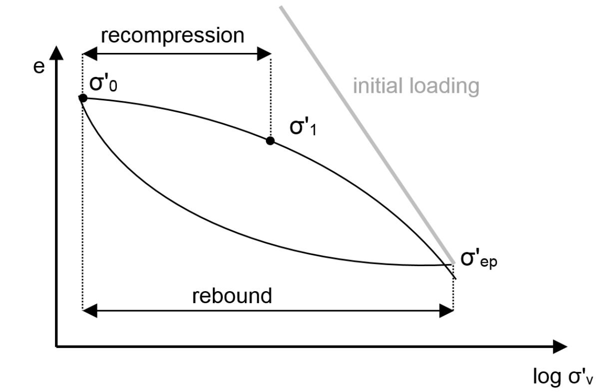

Fig. 6. Definition of recompression ratio RCR

Taking into account the unloading stress σ'_0, the RCR describes the of effective stress σ'_1 acting on a soil as a proportion of the preloading stress σ'_{ep}. It thus provides a geometric estimate of stress at any point on the *e*-log σ'_v path during reloading, in relation to the unloading difference.

Since the C_α/C_c concept also applies for the reloading phase, with $C_\alpha/C_c = C_{\alpha r}/C_{cr} = const$ (Tinat and Rosenberg 2016), the RCR has a linear relationship with both the quotient C_{cr}/C_c and $C_\alpha/C_{\alpha r}$.

$$C_{cr}/C_c = C_{\alpha r}/C_\alpha = \beta\ RCR \qquad \text{with } RCR < 1 \qquad (3)$$

Equation 3 enables an estimation of the recompression parameters based on the virgin compression parameters and stress history of unloading and reloading alone. The factor β is a soil mechanical parameter and dependent on the swelling index. The greater the swelling index of a soil, the greater the value of β.

The factor β is also affected significantly by the degree of consolidation of preloading. Figure 7 shows the linear correlation for the abovementioned tests, with coefficient of determination $R^2 > 0{,}98$ with the functional curves pass through the origin.

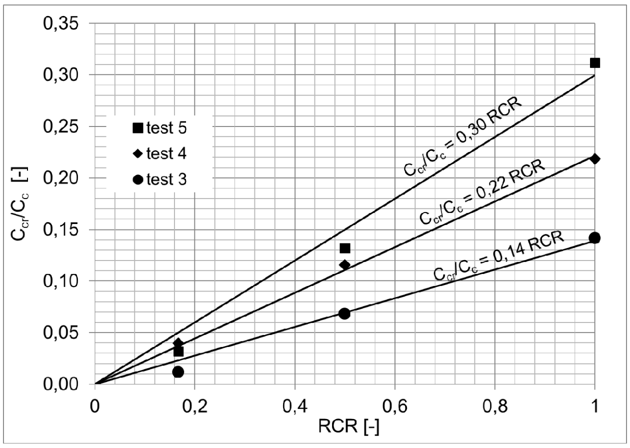

Fig. 7. Linear correlation between RCR and C_{cr}/C_c

Since the compression index C_c for clay was found to be near constant during virgin compression, C_{cr} and $C_{\alpha r}$ remained proportional to the RCR in all tests.

The degree of consolidation of preloading has a significant effect on the factor β and therefore also on the quotient C_{cr}/C_c. For the clay in question, the value of β ranged from 0.14 to 0.3, depending on the degree of consolidation of preloading. This means that, even with RCR = 1, when the effective preloading stress has been reached, the recompression parameters reached between only 14 and 30 % of the virgin compression parameters C_c and C_α. Once the preloading stress is exceeded, both parameters suddenly increase to 100 % of C_c and C_α.

According to assumptions of the RCR concept, the *e*-log σ'_v curve always displays the same geometric characteristic. The shape of the reloading path is thus not dependent on the magnitude of preloading stress, but rather on the unloading difference.

5 CONCLUSIONS

When preloading of soil is undertaken, both the consolidation behavior during preloading and recompression behavior during reloading are of interest. The residual settlements are especially influenced by long-term creep during reloading.

Secondary compression behavior under oedometric conditions can be described by $C_{\alpha r}$. $C_{\alpha r}$ is dependent on stress and time because of the law of compressibility by Mesri and Godlewski 1977 and the creep induced increase of equivalent stress.

The RCR can be used to estimate the coefficient of secondary compression if stress history and the value of C_α are known. The results show that a low recompression ratio RCR, in other words little reloading compared to unloading, will reduce creep. As the reloading stress approaches the primary consolidation stress, the coefficient of secondary compression approaches its original value during virgin compression. For the clay analyzed in this study a value of $C_\alpha/C_{\alpha r}$ = 0.14 to 0.3 was determined for RCR = 1. The values of peat were much bigger.

In order to realize effective and long-term mitigation of creep settlements, a significant unloading must occur after preloading. In standard preloading with voluminous landfills, this is only possible through extensive earthworks and heavy machinery. This is often not feasible in practice.

Ménard Vacuum Consolidation is an alternative method for achieving preloading stress and can be used in combination with standard surcharging. After switching the system off, significant unloading takes place and the RCR is greatly reduced.

In order to minimize residual settlements, it is recommended that construction activities should be adapted to reduce the RCR and that a high degree of consolidation is achieved during preloading.

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