Misconceptions about experimental substantiation of creep hypothesis A

Les idées fausses justifiant l'hypothèse A de fluage au laboratoire

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ABSTRACT: Ample laboratory experiments as well as field observations show existence of rate effects or creep during the primary consolidation phase of clayey soils. However, the role of creep during the primary consolidation phase has been a subject of active debate among researchers. As a result, two totally different hypotheses referred to as creep hypothesis A and B have been defined as a basis for the discussion. Despite being opposite extreme to each other, both creep hypotheses seem to be experimentally supported leading to confusion as to which of them is correct. This paper aims to consistently clarify the apparent misconceptions involved in the experimental substantiation of hypothesis A as well as discuss some of its unphysical implications. This means to provide simple and convincing arguments as to why creep hypothesis A is not experimentally substantiated. It is shown that cohesive soils behave in conformity with hypothesis B. It is also illustrated that a constitutive model based on hypothesis B can give excellent prediction of long-term field measurements of settlements and excess pore pressure responses.

RÉSUMÉ : De nombreuse observations sur le terrain et au laboratoire ont montré que le fluage existe au cours de la phase de consolidation primaire des argiles. Le rôle du fluage pendant la phase de consolidation primaire fait toutefois l'objet d'une vive controverse dans la littérature. Au cours des ans deux hypothèses complètement différentes ont été définies pour discuter du fluage dans les argiles ; l'hypothèse A et B. Les deux hypothèses semblent être soutenues par des résultats en laboratoire et cela mène à savoir laquelle des deux est correcte. Le but de cette étude est de clarifier certaines idées fausses concernant l'hypothèse A basé sur des résultats expérimentaux. Ceci vise à renforcer les arguments qui montre que l'hypothèse A n'est pas valide. L'étude montre également que les sols cohérents se comportent pratiquement de la façon d'écrite par l'hypothèse B. Finalement, un modèle de comportement basé sur l'hypothèse B produit des résultats qui concordent très bien avec des mesures de tassements en chantier ainsi qu'avec la réponse des pressions interstitielles due à la charge.

KEYWORDS: Creep, primary consolidation, settlement, clays

1 INTRODUCTION

Settlement of saturated soils under increased loading consists of two successive phases, commonly referred to as the primary and secondary consolidation phases. The primary consolidation phase is dominated by pore pressure dissipation and effective stress increase; whereas, the secondary consolidation phase is dominated by creep at almost constant effective stress.

The existence of creep during primary consolidation is evident, but there exist opposing opinions on the role of creep in the primary consolidation phase. In 1977, Ladd et al. formally proposed two creep hypotheses referred to as creep hypotheses A and B. Creep hypothesis A implies that the end of primary consolidation (EOP) strain and EOP preconsolidation stress (p'_c) are unique, independent of the consolidation duration; while, hypothesis B implies that the EOP strain increases or EOP p'_c decreases with increasing duration of the primary consolidation.

The two creep hypotheses have significance implications when it comes to practical applications such as prediction of field settlements where settlement behaviours of laboratory tests (short primary consolidation duration) have to be extrapolated to describe in-situ performance of clay deposits with very long primary consolidation duration. Mesri (2003) and Leroueil (2006) summarised several experimental and numerical substantiations that have been independently presented to advocate the two hypotheses. However, these voluminous substantiations had little effect in deciding which of the two hypotheses was correct as experimental observations were presented that seem to advocate two opposing soil behaviours.

2 SUBSTANTIATIONS OF THE CREEP HYPOTHESES

The substantiations and arguments for hypothesis B are more general as compared to the extreme hypothesis A which says that the EOP strain and p'_c are identical irrespective of the time it takes to reach an EOP state. Hence, this motivates to take a closer look at the experimental substantiation of hypothesis A. Four groups of substantiations have been put forward by the advocates of hypothesis A (Mesri, 2003). These arguments can briefly be stated as; (1) comparing EOP strain of specimens with different heights (here 127 and 508 mm thick specimens), (2) studying sub-specimen compressibilities in interconnected tests (3) predicting field settlements and excess pore pressures using a numerical model developed based on hypothesis A concept (referred to as ILLICON methodology) and (4) comparing field and laboratory preconsolidation stresses.

Degago et al. (2009, 2010, 2011a and 2011b) and Degago (2011) have thoroughly investigated the experimental and numerical substantiations of hypothesis A and provided explanations using a consistent framework as to why hypothesis A seemed to be wrongly substantiated. Actually, the very same data have been used to substantiate hypothesis B. However, recent work by Mesri and Feng (2009) (published in 2011) indicates a series of misconceptions by the advocates of hypothesis A regarding substantiation of hypothesis A. Therefore this paper attempts to briefly provide clarifications for most of these misconceptions. In addition, it presents some of the recent works performed with regard to the experimental and numerical substantiations of the two creep hypotheses.

3 SOME NUMERICAL ASPECTS

The isotache concept, proposed by Šuklje (1957), can conveniently be used for modeling rate dependency of clays. The isotache concept states that there is a unique relationship between the current strain rate (change in void ratio), effective stress state and strain (void ratio).

Under oedometer testing conditions, a direct implication of the isotache concept is that the experienced p'_c is dependent on the time between the load increments, or the rate of loading. Under EOP incremental loading scheme, the implication of the isotache concept is sketched in Figure 1 for fast and slow consolidation durations and the experienced p'_c is shown to be rate dependent. In opposition to this, hypothesis A implies a unique EOP effective stress-strain relationship irrespective of consolidation duration (Mesri and Choi, 1985b). Hence, the distinction between the two hypotheses basically comes down to whether the resulting p'_c is rate dependent or not.

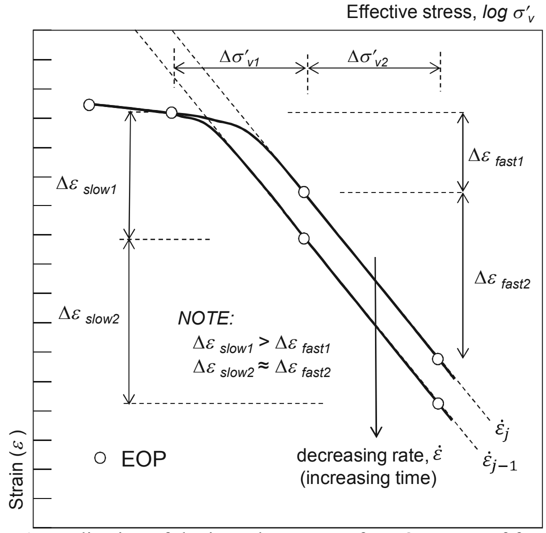

Figure 1. Implication of the isotache concept for EOP states of fast and slow consolidation times under incremental loadings up to EOP states.

In the isotache concept the strain rate is determined by the current void ratio and effective stress. In water-saturated soil, change in void ratio can only take place when water is expelled from the soil. Therefore the strain rate is indirectly controlled by the global consolidation process. However, a soil element inside a soil layer (or sample) has neither any direct information of this global consolidation process nor remaining time until the EOP consolidation state is reached. However, for hypothesis A to hold true, the response in all soil elements must be a function of this remaining time and its advocates argue that "no sub layer, including the drainage face, experiences any secondary compression until the simultaneous completion of primary consolidation of all sub layers" (Mesri and Vardhanabhuti 2006). Such assertion, however, violates some basic axioms of continuum mechanics such as axiom of *material invariance* and axiom of *objectivity* (see e.g. Eringen (1967)).

4 SOME MISCONCEPTIONS AND CLARIFICATIONS ON SUBSTANTIATIONS OF CREEP HYPOTHESIS A

Degago et al. (2009) re-evaluated the EOP experiments conducted on 127 and 508 mm thick specimens by Feng (1991) and showed that the experiments actually substantiate hypothesis B. In addition, Degago et al. (2009) used a numerical tool based on hypothesis B to analyse the raw data of the tests as they were originally conducted and showed that they are explainable using this model. Mesri and Feng (2009) questioned the validity of hypothesis B and attempted to provide an explanation for their tests. However, a series of misconceptions are visible in Mesri and Feng (2009) that needs clarifications and these are given in the following sections by classifying the apparent misconceptions into laboratory and field studies.

4.1 *Laboratory studies*

As illustrated in Figure 1, the specific load increment that starts below initial p'_c and exceeds it is critical. This has been treated in greater detail in Degago et al. (2011a). Degago et al. (2009) focused on this increment and showed that the tests conducted by Feng (1991), on the 127 and 508 mm thick specimens of Batiscan and St. Hilaire clays, did not have the same EOP state.

To determine if there is any possibility that hypothesis A has a practical use, evidences for hypothesis A must be found. This requires first of all giving an objective definition of time at the end of "primary consolidation". The obvious criterion would be the remaining excess pore pressure. However, this requires a detailed knowledge on the excess pore pressure. Mesri and Feng (2009), referring to Mesri et al. (2005), admit that such an exact criterion does not exist.

Mesri and Feng (2009) claim that Degago et al. used "micro-management" to evaluate the EOP criterion adopted in the test by Feng (1991). However, a clear criterion is exactly what one needs for answering this fundamental question, especially to study the validity of hypotheses A where EOP is a key state. With this regard, it is worthwhile to mention that EOP definition is not important for hypothesis B where there is a smooth transition from primary to secondary consolidation phases. Still, it is important to understand the nature of excess pore pressure around EOP state where creep starts to dominate and governs the dissipation of the remaining excess pore pressure. At this stage, the soil can continue to deform without a significant change in excess pore pressure. Consequently, the EOP criteria can easily be misused and there is a potential of exposing specimens being compared to unsystematic creep durations. In such cases, comparisons may end up being not genuine enough to reflect reality. The excess pore pressures for the 127 and 508 mm thick specimen of Batiscan clay were 0.1 and 0.8 kPa and for St. Hilaires clay they were 1.0 and 2.2 kPa, respectively. Under these conditions one cannot claim that the thin and the thick specimen have had the same EOP state.

One fundamental proof that was overlooked in the discussion of Mesri and Feng (2009) is time considerations aspects. From the classical consolidation theory, the ratio of the time needed to achieve the same degree of consolidation between two specimens is equal to the square of the ratio of the heights. However, because of the consolidation time being increased by creep, a thick specimen would need more time than the one calculated based on the classical consolidation theory concept. Accordingly, one can compare the time needed to achieve EOP state for the 127 mm (t_{127}) and 508 mm (t_{508}) thick specimens studied by Feng (1991). In fact the ratio t_{508}/t_{127} in the actual tests of Batiscan and St. Hilaire clay were only 7 and 9 instead of being larger than 16. Therefore the tests do not even qualify as tests conducted in accordance to hypothesis A where the ratio t_{508}/t_{127} is expected to be equal to 16 (Ladd et al., 1977).

Based on the final excess pore pressure of the 508 mm thick specimen, Degago et al. (2009) established the time that corresponds to the same EOP state of the 127 mm thick specimen. This gave a ratio t_{508}/t_{127} of 19 and 20 for both clays (>16), and most importantly an EOP strain that increases with specimen thickness. Figure 2 shows details of the excess pore pressure and volumetric strain development of St. Hilaire clay, for the step of interest, for both sample thicknesses. It is seen that a small variation in excess pore pressure gives significant difference in the "primary consolidation" duration and the corresponding strains. To achieve same EOP criterion with the 508 mm sample, the 127 mm sample should have been loaded for 14 days instead of the actual 33 days adopted in the tests.

Mesri and Feng (2009) present two figures of excess pore pressure versus time for Batiscan clay to show that sufficient time is given for the 508 mm thick specimen to reach EOP. The stress increments they presented were for a step well before the initial p'_c and for a step after exceeding the initial p'_c. However, they did not present the most important step, i.e. the step that starts below and exceeds the initial p'_c. Here lies the main misconception, as Mesri and Feng (2009) tend to continue to underrate the importance of the load increment that exceeds the initial p'_c.

Applying the interpretation shown in Figure 2, the resulting stress-strain relationship of the St. Hilaire clay is shown in Figure 3. The interpreted experimental data clearly imply hypothesis B, unlike the original curves where inconsistent EOP criteria were used to wrongly advocate hypothesis A. Mesri and Feng (2009) wondered about the re-interpretation of the load increment after exceeding p'_c (the broken lines in Fig 3). However, referring to the broken line in Figure 3, Degago et al. (2009) clearly stated "a similar re-interpretation procedure could not be adopted for the following steps since the thin specimen has already exceeded its EOP condition". To establish the broken lines Degago et al. (2009) simply used the fact that, after exceeding p'_c, the incremental strain for a thin and thick specimen are almost the same, see Figure 1.

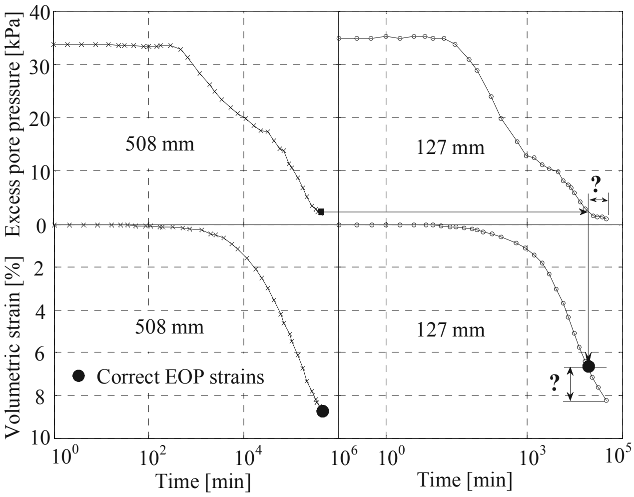

Figure 2. Re-evaluation of experimental results of St. Hilaire clay for the load increment that exceeds p'_c (raw data after Feng, 1991)

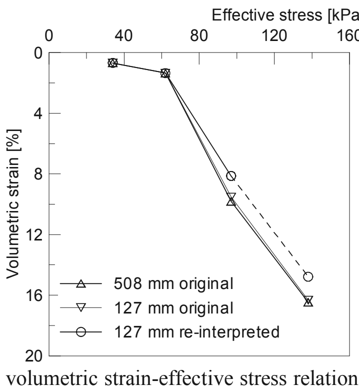

Figure 3. EOP volumetric strain-effective stress relationship of thin and thick specimen of St. Hilaire clay for the load increment that exceeds p'_c (raw data after Feng, 1991)

Regarding soil element compressibility, Degago et al. (2010) conducted a test to show that a soil element close to the drainage boundary does not wait for the global EOP state before starting secondary compression. This was also found when Degago et al. (2011a) revisited the sub-specimen nominal strain versus time relationships of the 508 mm samples of Batiscan and St. Hilaire clay conducted by Feng (1991). For the step exceeding the initial p'_c, the tests showed largest deformation on the sub-specimen closest towards the drainage boundary. This is in accord with predictions by the isotache concept and contrary to the claims made by Mesri and Vardhanabhuti (2006).

4.2 *Field studies*

Mesri and Feng (2009) argued that "the computer program based on Soft Soil Creep (SSC) model should be applied to field situation with primary consolidation duration of 30 to 50 years before reaching any general conclusion on EOP compression and on the uniqueness of preconsolidation pressure". In addition they presented excellent settlement predictions of field cases to illustrate the validity of hypothesis A. In connection to this, Degago et al. (2011b) studied 57 years of settlement data from the Väsby test fill and have clarified two misconceptions observed in the arguments by Mesri and Feng (2009) regarding their field predictions. First, it was clearly illustrated that the excellent settlement predictions and somehow lower excess pore pressure predictions by ILLICON were due to use of soil data from highly disturbed samples along with inappropriate analysis assumption. Secondly, it was demonstrated that when one interprets soil data from high quality samples then the isotache model (SSC) gives excellent settlement as well as excess pore pressure predictions, see Figure 4 and Figure 5.

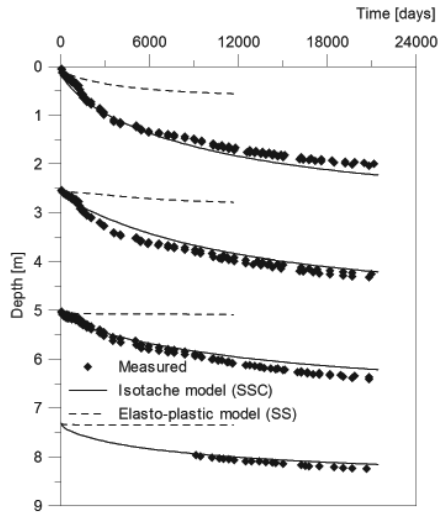

Figure 4. Time-displacement curves for different depths (Degago et al. 2011b)

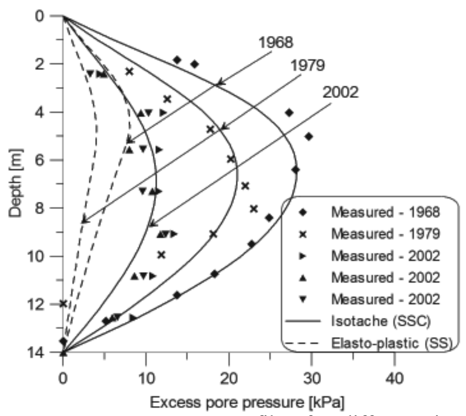

Figure 5. Excess pore pressure profiles for different times plotted against undeformed soil layer depth (Degago et al. 2011b)

A typical oedometer test used in the analysis of Väsby test fill by ILLICON (Mesri and Choi, 1995a) had an EOP overconsolidation ratio (OCR) value of 1.3 as compared to the more correct value of 1.8 interpreted from high quality block samples (Leroueil and Kabbaj 1987). The implication of this is that, had Mesri and Choi (1985a) used high quality data, ILLICON would have significantly under predicted both the excess pore pressure and the settlement measured at the Väsby test fill. In addition, Mesri and Choi (1985a) also ignored an important role of buoyancy in large deformations. In the time period analyzed by Mesri and Choi (1985a), a 42% load reduction was estimated due to buoyancy effect. This effect is too large to be neglected. Taking into account this key aspect would have even led ILLICON to further underestimate measurements in a similar manner to the results of the elasto-plastic model (SS) shown in Figure 4 and Figure 5.

In connection to another field aspect, Mesri and Feng (2009) also present a summary data, detailed in Mesri et al. (1995), claiming that field and laboratory vertical preconsolidation stresses (σ'_p) are the same. The authors of this paper found it difficult to access these data in Mesri et al. (1995), in order to analyze the quality of the test data (e.g. sample disturbance effects) and to assess how and which procedures are used in the determination of σ'_p's, see further discussion in Degago (2011). An exception to this was the data by Sällfors (1975) which constitutes one third of the data gathered by Mesri et al. (1995). Therefore the authors have thoroughly looked into the laboratory and field σ'_p data as presented in Sällfors (1975).

A good starting point to evaluate the data by Sällfors is to understand the background behind the data. Sällfors studied and determined field σ'_p based on pore pressure response to an applied stress increment. Then he proposed a method to directly predict the field σ'_p based on laboratory CRS tests. Because of the background and aim of the method, the σ'_p interpreted in this way would naturally give a σ'_p lower than those determined for laboratory cases (Olsson, 2010). In simple terms, the good match between laboratory and field σ'_p of Sällfors (1975) merely show that the Sällfors method serves its purpose. However, Mesri et al (1995) took the final data and made a wrong conclusion and this may relate to a lack of understanding of the objective behind the data gathered by Sällfors (1975).

5 SUMMARY OF THE MAIN MISCONCEPTIONS

The most important misconceptions as observed in the works of the advocators of hypothesis A arises from overlooking some important aspects of clay compressibility. These are discussed in detail in this paper and are briefly summarized as follows:

1. The importance of the load (effective stress) increment that starts below and exceeds the initial p'_c has not been considered and understood properly by the advocators of hypothesis A and its role has continually been underrated.
2. Without a unique and consistent EOP criterion, the results from samples with different specimen heights can be interpreted inconsistently resulting in misleading conclusions. The discrepancy is not necessary significant within the duration of laboratory tests, but become important when extrapolating to field condition. EOP is of no interest when using a model based on hypotheses B as it gives a smooth transition between primary and secondary consolidation phases.
3. Effect of sample disturbance needs proper assessment. Successful prediction of long-term field performance demands use of high quality data with creep considerations. However, by using results from tests on highly disturbed samples and disregarding creep, one may obtain reasonably good estimate of settlements.

6 FINAL REMARKS

Degago et al. (2009, 2010, 2011a and 2011b) and Degago (2011) clearly showed that there exist definitive data to demonstrate that the creep hypothesis B agrees very well with the measured behaviour of cohesive soils. It is also illustrated that that the isotache approach describes this soil response properly. In closure, the main points of these studies with regard to this paper are briefly stated as follows;

1. The experienced preconsolidation stress as well as EOP strain are rate dependent even for EOP loading conditions and this fact has been experimentally supported by several EOP tests and field observations. All the experimental evidences that were used to wrongly advocate hypothesis A actually imply hypothesis B.
2. Hypothesis A would require that the soil element close to the drainage boundary would wait for the global EOP state before staring its secondary compression. However, various tests conducted on sub-specimen compressibility clearly showed that this does not hold true and the compressibility of a soil element is controlled by prevailing conditions at that particular element rather than what is happening elsewhere.
3. A model based on the isotache approach gives excellent agreement between field measurement and numerical simulations when soil data are derived from high quality samples along with appropriate analyses assumptions.
4. Future developments related to the compressibility of natural clays, such as modeling anisotropy and destructuration effects, should be based on the isotache framework (hypothesis B) along with use of soil data from high quality samples.

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