The non-uniqueness of the end-of-primary (EOP) void ratio-effective stress relationship

La non-unicité de la courbe indice des vides-contrainte effective à la fin de la compression primaire

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ABSTRACT
How to extrapolate creep behaviour of soft clays from a thin laboratory specimen to a thick in-situ soil layer is one of the key research topics in understanding the fundamentals of clay compressibility. Investigation of whether the end-of-primary (EOP) void ratio-effective stress relationship is unique or not is a central part of this research. There have been several discussions and active debates for and against the uniqueness concept. However, most of the arguments against the uniqueness concept have mainly been based on discussing theoretical assumptions rather than explaining experimental observations. In this paper, selected experimental results that seemed to illustrate the uniqueness concept are thoroughly studied. These measurements are re-evaluated and the tests are analyzed numerically. This work shows that the end-of primary void ratio (strain)-effective stress relationship is not unique. The study also supports the view that soil compressibility is well described by the Isotaches concept.

RÉSUMÉ
L'extrapolation du comportement au fluage des argiles molles entre un petit échantillon au laboratoire et une couche épaisse de sol in situ est un sujet de recherche clé pour la compréhension des principes fondamentaux de la compressibilité des argiles. Cette recherche a pour but principal de déterminer si la relation entre l'indice des vides et les contraintes effectives à la fin de la compression primaire est unique ou pas. De nombreuses discussions et débats ont eu lieu autour de ce concept d'unicité. Cependant la plupart des arguments allant contre ce concept d'unicité se sont basés sur des discussions autour d'hypothèses théoriques plutôt que sur des observations expérimentales. Dans cet article, une sélection de résultats expérimentaux ont été consciencieusement étudiés afin d'illustrer le concept d'unicité. Ces mesures ont été réévaluées et analysées numériquement. Ce travail montre que l'indice des vides (déformation) à la fin de la consolidation primaire n'est pas unique. Cette étude supporte le concept des Isotaches se voulant une bonne description de la compressibilité des sols.

Keywords : Primary compression, secondary compression, Isotaches concept

1 INTRODUCTION

Settlements of thick *in-situ* soil layers are predicted based on extrapolation of experimental results that are derived from thin laboratory specimens. How to extrapolate results from fast laboratory tests to slow field processes has been and still is one of the key research topics for understanding the basics of soil compressibility.

In their state-of–the-art report, Ladd et al. (1977) raised an important question related to creep during primary compression. The fundamental question was whether or not creep acts as a separate phenomenon, during primary compression, while excess pore pressure dissipates. If it does, then for a given effective stress change, the end-of-primary (EOP) compression strain depends upon the duration of the consolidation phase and hence the thickness of the clay layer. Such consideration led to realization of two possible extreme effects of sample thickness which were termed Hypothesis A and B by Ladd et al. (1977). Hypothesis A is a case where the EOP strain is the same irrespective of the thickness of the consolidating soil layer (consolidation period). Whereas, Hypothesis B predicts an increase in EOP strain with increasing consolidation period as a result of creep effects. Admitting that Ladd et al. (1977) themselves were biased towards Hypothesis A, they conclude that "*little definitive data exists to show which of the two hypotheses is more nearly correct for the majority of cohesive soils*". Since 1977, this concern continues to be a topic of active discussion among various researchers and remains to be an issue that needs to be settled.

2 UNIQUENESS OF EOP VOID RATIO

The uniqueness of end-of-primary [EOP] void ratio-effective stress relationship implies that for any natural soils the EOP void ratio-effective stress curve obtained from a thin laboratory specimen is valid independent of the duration of the consolidation period. Hence a single EOP void ratio-effective stress curve represents the behaviour of both a thin laboratory specimen and a thick in-situ soil layer (Mesri & Godlewski 1979, Choi 1982, Mesri & Choi 1985, Feng 1991, Mesri 2003).

The validity of having a unique EOP void ratio-effective stress relationship has been viewed from two perspectives by different groups of researchers. Early works by various researchers working on creep (e.g., Šuklje 1957, Bjerrum 1967, Janbu 1969, Šuklje 1969 and others) described creep rate to be given by the current effective stress and the current reference strain. In these formulations the EOP void ratio is dependent on the thickness of the consolidating layer; hence, imply Hypothesis B. On the other hand, if creep is totally disregarded during consolidation, a unique the EOP void ratio is obtained irrespective of consolidation period. Hence the uniqueness of EOP can be viewed as a direct consequence of an assumption that disregards creep during primary compression (e.g., Yin & Graham 1990, Jamiolkowski et al. 1985 and Leroueil 2006). However, other researchers (Mesri & Godlewski 1979, Choi 1982, Mesri & Choi 1985, Feng 1991, and Mesri 2003) came up with experimental observations where the EOP void ratio (strain) seemed to be independent of the consolidation period. This group of researchers supports that creep takes place during

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-324

primary compression; however the creep contribution is controlled by stress rate. Their argument can be described by the subsequent statements. Soil compression is caused by two interrelated contributions, namely due to change in effective stress as well as due to time. The contributions of these two components vary according to the prevailing effective stress rate. Hence, the effective stress rate difference that exist between thin and thick soil layers, is claimed to affect the corresponding compression components such that the EOP void ratio is independent of the consolidation period.

Most of the arguments raised against the uniqueness of EOP strain were mainly based on discussing theoretical assumptions rather than explaining experimental observations that seem to support a unique EOP; due to this, these arguments lack a cutting edge. In this paper, selected experimental results that were used to validate the uniqueness concept are thoroughly studied.

3 EXPERIMENTAL OBSERVATION AND EVALUATION

In 1976, the University of Illinois at Urbana Champaign initiated a laboratory research program to investigate the validity of the uniqueness concept. Details of these laboratory investigations can be found in Mesri and Godlewski (1979), Choi (1982) and Feng (1991). Review of existing data along with test results have been presented by Choi (1982) and later by Mesri and Choi (1985), to claim the validity of the concept of unique EOP void ratio-effective stress relationship. Similar experiments conducted by Feng (1991), with additional and enhanced measurements, were used to further confirm the uniqueness of the EOP void ratio concept. In the current paper, these experimental observations are evaluated and the validity of the uniqueness concept is critically assessed.

3.1 *End-of-primary loaded tests*

A reliable and straightforward way to investigate the uniqueness of EOP strain is to perform compression tests on specimens of different thickness with an EOP loading procedure, In EOP tests, loads are applied when the excess pore pressure is dissipated according to the defined EOP criterion. However, during the secondary compression phase, where the effective stress is practically constant, there is still minor excess pore pressure due to creep deformations. The excess pore pressure in this phase is generally small and it could take a considerable amount of time before it is completely dissipated. Theoretically it will never be zero as long as there is soil compaction. Hence, it is very important to establish a consistent criterion that defines the end of primary consolidation.

3.2 *Test set up and description*

Feng (1991) has conducted a series of successful EOP tests on thin (125 mm) and thick (500 mm) specimen of Batiscan and St. Hilaire clay. The diameter of both specimens was 63.5 mm. Four 125 mm thick specimens have been interconnected in series to yield the equivalent 500 mm thick specimen. All the tests have been conducted in triaxial equipment under three dimensional isotropic compressions and one dimensional drainage condition. Measurements during the test include volume of water expelled and top axial deformations versus time of each specimen. Results of the test measurements, for both the thin and thick specimens, are presented in Figure 1 using solid line curves (after Feng, 1991). These results indicate that a single curve more or less represent both the thin (125 mm) and the thick (500 mm) specimen. Hence, these experimental observations, along with other similar laboratory tests and field cases, have been used to support the EOP uniqueness concept (Mesri 2003).

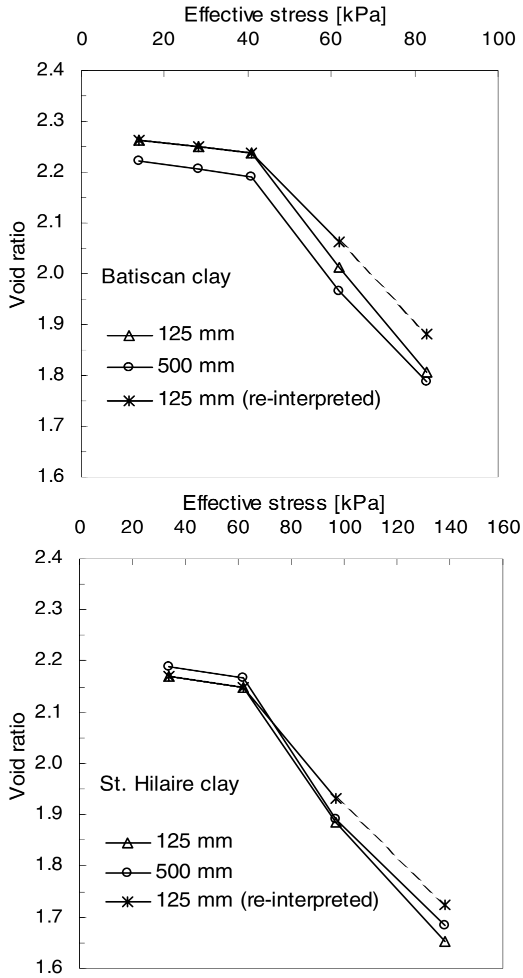

Figure 1. Experimental measurements along with re-interpretation (raw data after Feng, 1991)

3.3 *Evaluation of test results*

The stress increments before crossing the preconsolidation stress yield small deformation compared to the increments that followed. The first significant effect of creep is observed for the stress increments that span the preconsolidation stresses, p'_c. Hence special attention is given for this step and the adopted EOP criterion is evaluated.

The classical Terzaghi′s consolidation theory disregards creep during the consolidation phase. This theory, for the same drainage condition and type of soil, relates the consolidation duration of a thin laboratory specimen to a thick in-situ soil layer based on the square of the ratio of the two thicknesses. However, a large number of laboratory and field observations have shown that creep does also occur during consolidation delaying the dissipation process (Leroueil 2006). The implication of this is that the consolidation duration of a thick specimen is underestimated by predictions according to the classical consolidation theory. However, such predictions can be used to establish lower bound values. Hence, for the tests conducted by Feng (1991), the ratio of the consolidation duration of the two specimens is expected to be a minimum of at least 16 for the same load step. For the step spanning p'_c, the ratio of the actual ratios for the durations of the thick and the thin specimen were 7 and 9 for Batiscan and St. Hilaire clay, respectively.

Strictly speaking, it is the degree of dissipation of the excess pore pressure that should establish a true EOP criterion. The final value and the degree of dissipation of the excess pore pressure have been studied for the step spanning p'_c. It was found that the excess pore pressure of the thin and the thick specimen, for Batiscan clay, were 0.1 kPa (or 99.5% of the applied load increment) and 0.8 kPa (or 96.2% of the applied load increment), whereas for St. Hilaire clay, it was 1.0 kPa (97.2%) and 2.2 kPa (93.6%).

Small difference in the final excess pore pressures has significant effect on the EOP strain as creep governs the dissipation process. Hence, the experimental measurements of Feng (1991) have been re-interpreted such that the same final excess pore pressure or the same degree of excess pore pressure is adopted for both the thin and the thick specimen. This demanded the volumetric strain of the thin specimen of Batiscan and St. Hilaire clay to be determined at 96.2% and 93.6% of excess pore pressure dissipations, respectively. After re-interpretation of these test results for the same degree of dissipation, the time ratio of thin to thick specimen were 19 and 20 for Batiscan and St. Hilaire clay, respectively. Note that both ratios are greater than 16 as anticipated. A similar re-interpretation procedure could not be adopted for the following steps since the thin specimen has then already exceeded its EOP condition. Nevertheless, the step after spanning p'_c, has been predicted as shown with broken lines (Figure 1) using concepts derived from the Isotaches concept (Šuklje 1957, 1969). The measured volume changes of the 125 mm thick specimen were re-evaluated, such that the same EOP criterion is adopted as in the 500 mm thick specimen. After this re-interpretation, it can be seen (Figure 1) that both the curves are different and suggested a non unique EOP void ratio effective stress relationship.

4 NUMERICAL STUDY

Having first studied some details of the experimental observations of Feng (1991), the next step was to numerically study some of the observed behaviors. The finite element code PLAXIS was used for this purpose. The material model used is the Soft Soil Creep (SSC) (Stolle et al. 1999). The model incorporates creep during the consolidation process and yields a non-unique EOP strain for different specimen thicknesses. The vertical strain was considered instead of the volumetric strain due to uncertainties in the volumetric strain of the individual specimens and most importantly due to possible anisotropic response of the actual clay.

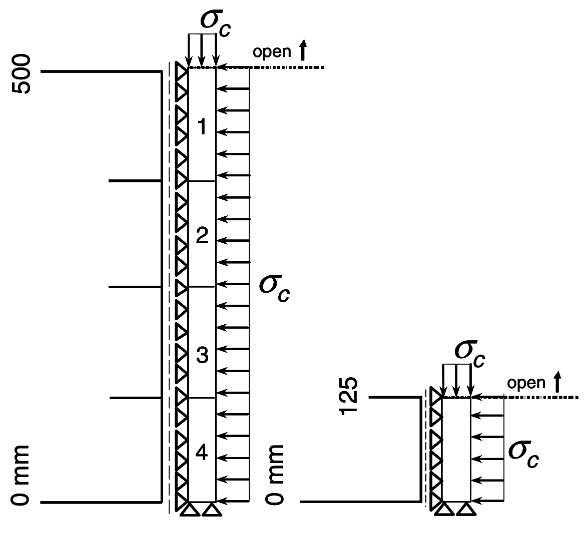

Figure 2. Axisymmetric FE-model of the triaxial specimens

Soil specimens of 125 and 500 mm thick with a diameter of 63.5 mm were simulated under isotropic triaxial loading condition and one way drainage possibility. A very fine mesh of 15 noded elements was adopted under an axisymmetric condition. Incremental loading schemes were adopted as in the actual experiments. Hence, the applied isotropic stresses, σ_C, for Batiscan clay simulation were 14, 28, 41, 62, 83 and 125 kPa and for St. Hilaire clay simulation they were 35, 62, 97 and 138 kPa. The time durations of each load increment in the simulation were similar as in the actual experiment. The geometries of the thin and the thick specimen used in PLAXIS are shown in Figure 2.

The soil parameters used in the simulation (Table 1) are based on the abundantly variety of other tests conducted by Feng (1991). Identical set of soil parameters were used for simulation of the thin and the thick specimen.

Table 1. Soil parameters adopted for SSC (based on Feng, 1991)

Soil parameters & [units]	Symbol	Values	
		Batiscan clay	St. Hilaire clay
Permeability [m/day]	k_v	8×10^{-5}	6×10^{-5}
Change of permeability [-]	Δc_k	1.05	1.10
Modified swelling index [-]	κ*	0.0063	0.014
Modified compression index [-]	λ*	0.200	0.227
Modified creep index [-]	μ*	0.0062	0.0068

According to the Isotaches concept (Šuklje 1957, 1969), any distinction between thick and thin specimen is revealed through the respective preconsolidation stress, p'_c. Hence, simulation results of the three load increment steps in the vicinity of p'_c, i.e. the step before p'_c, spanning p'_c, and after p'_c are presented together with the laboratory data (Figure 3 and Figure 4). The experimental measurements and simulation results of the top axial displacements during each step are normalized by the original height of the corresponding specimen to yield the incremental vertical strains plotted against time.

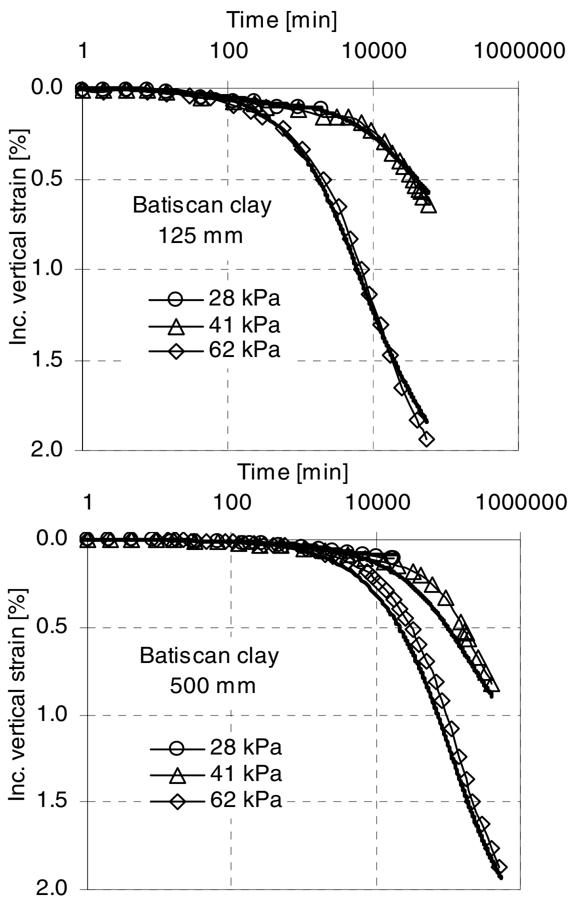

Figure 3. Numerical simulation (smooth bold lines) versus experimental measurements (lines with symbols) of Batiscan clay.

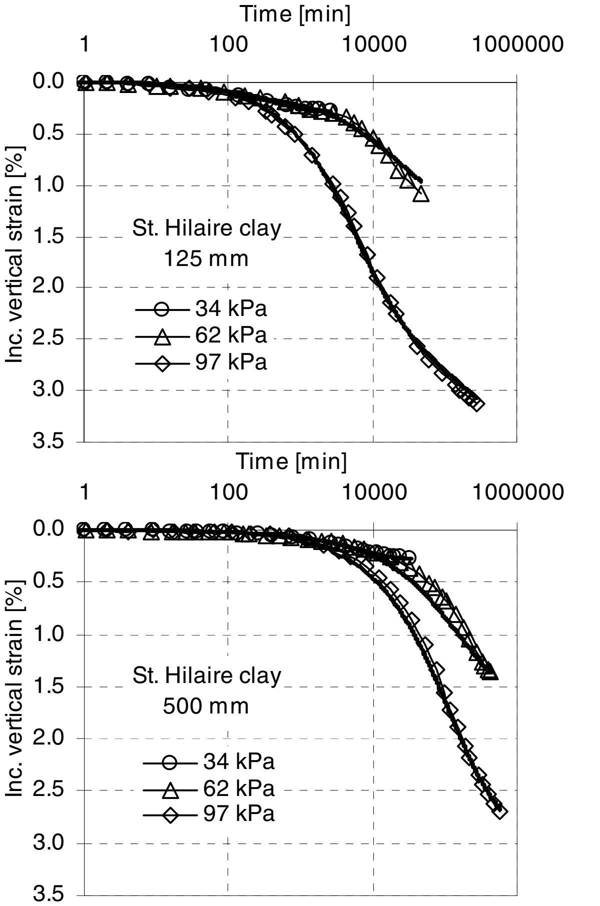

Figure 4. Numerical simulation (smooth bold lines) versus experimental measurements (lines with symbols) of St. Hilaire clay.

5 DISCUSSIONS

The assumption of having a unique EOP for a thin laboratory specimen and a thick in-situ soil layer must imply that either creep is disregarded during consolidation or the creep contribution is identical in both the laboratory and the in-situ soil layer, irrespective of the totally different duration of the primary consolidation phase.

The re-interpretations of the measured results have shown that it is of vital importance to use a consistent EOP criterion. Evaluations of experimental data have shown that either the time for the thick specimen has been too short or the time for the thin specimen has been too long. The consolidation period of the thick specimen had already taken years and it may seem unnecessary to wait for longer time; but what could have been done was to avoid the thin specimens from consolidating longer than necessary. Under the actual test condition, the EOP void ratio seemed unique as in Hypothesis A, but re-evaluation of the measurements gave different results that support Hypothesis B.

Only when considering the incremental strain (or change in void ratio) during the load step after the preconsolidation stress there seems to be a unique result for both the thin and the thick specimen. However, this is not valid for a general stress history.

Numerical simulations using the Soft Soil Creep (SSC) gave very good agreements between measured and calculated results. SSC is based on the Isotaches concept that considers creep during the primary and the secondary compression phases and therefore yields a non-unique EOP void ratio/strain. It is seen, Figure 3 and Figure 4, that the SSC model captures the experimental measurements well. However, for more general stress conditions, the model needs further developments in order to include effects such as destructuration and anisotropy.

6 CONCLUSIONS

The non-uniqueness of end-of-primary (EOP) void ratio (volumetric strain) versus effective stress relationship has been demonstrated using experimental measurements that have been used earlier by others to support the uniqueness concept. Detailed studies of raw data with direct comparisons of results from thin and thick specimens using a consistent EOP criterion have showed that the EOP void ratio is dependent on the thickness of the specimen. Hence, the EOP void ratio versus effective stress curve of a thicker specimen is larger than for a thinner specimen.

The formulation of creep in the Isotaches concept gives a non-unique EOP void ratio-effective stress relationship. This study illustrated that the measured results can be calculated, by the same set of input parameters for the thin and the thick specimen, using a soil model that is based on the Isotaches concept.

Future developments related to clay compressibility should therefore be focused on enhancing models that naturally yield a non-unique EOP void ratio–effective stress relationship. Parts of the important extensions include modelling anisotropy and structure effects.

ACKNOWLEDGEMENT

The International Center for Geohazards (ICG) is gratefully acknowledged for providing all the necessary supports during the research.

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