Preparation of stiff overconsolidated clay samples for the study of soil deformations around tunnels

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Abstract: Soil samples for laboratory testing range from 'undisturbed' and remoulded samples to reconstituted samples prepared from slurry. For the latter, artificially prepared soils are commonly used due to their well known properties. Amongst these, Speswhite kaolin is used in UK for both fundamental and applied research. The preparation of reconstituted samples generally involves K_o-consolidation in an attempt to reproduce the geological formation of a natural soil. Various procedures have been used, but not much has been published about their relative merits, detailed characteristics and implementation difficulties. Any of these procedures generally involves either one phase, where the one-dimensional consolidation is completely performed in a consolidation device, or two phases involving the last stages of the consolidation being carried out inside a triaxial cell. Whichever option is used, the processes of extrusion, trimming and installation of the sample into the triaxial cell have a similar effect to those suffered by 'undisturbed' core specimens where the mean effective stress (p′) is inevitably modified. The findings presented in this paper are part of a research project evaluating whether the use of some of the available constitutive models is appropriate or not for the analysis of soil behaviour around deep single and twin tunnels. The study involves finite element analysis, conventional triaxial testing and stress path testing using a computer-controlled hydraulic cell. The reasons for preparing reconstituted samples in this case and the requirements in terms of stress conditions and stiffness are reviewed. This paper summarizes some of the methods that have been used for the one-dimensional consolidation of slurries and describes in more detail the ones considered for the current project, for which the observed limitations are discussed. Alterations occurring to the specimen when being moved from the consolidation device to the triaxial cell are also discussed.

Résumé: Pour réaliser des tests en laboratoire, trois sortes d'échantillons de terre ont été constitués, échantillon de terrain intacte, remoulée et échantillon reconstituée à partir de mixtures semi liquides. Pour les échantillons reconstitués, la terre artificiellement traité est choisie du fait de ses propriétés bien connues et le Speswhite kaolin a été utilisé en Grande Bretagne pour les deux recherche appliquée et fondamentale. La formation naturelle géologique du sol a été reproduite en utilisant, dans la préparation des échantillons reconstitués, le processus de K_o-consolidation. Diverses procédures ont été utilisées pour la préparation de ces échantillons mais il existe peu de publication sur leurs propriétés, leurs caractéristiques détaillées et sur les difficultés de leur application. Chacune de ces procédures compris une phase où la 1D-consolidation est effectué complètement dans un appareil de consolidation, ou deux phases avec la réalisation des dernières étapes de la consolidation à l'intérieur de la chambre triaxial. Quelque soit les moyens utilisés ; le procédé d'extrusion, le dégraissage ou la mise en place de l'échantillon dans la chambre triaxial, les effets sont similaires à ceux subis par l'échantillon de terre intact dont la moyenne effective du stress (p') est inévitablement modifiée. Les découvertes présentées dans cet article font parties d'un projet de recherche évaluant l'utilisation des modèles constitutifs disponibles pour l'analyse du comportement du sol autour de tunnels profonds simples ou doubles. Cette étude implique analyses des éléments finis, conventionnel triaxial tests et tests de trajectoire de stress utilisant une hydraulique chambre ordinateur-commandé. Les raisons du choix de la préparation des échantillons reconstitués pour cette recherche, les exigences en termes de contraintes et de rigidités seront développées dans cet article qui reprend quelques unes des méthodes utilisées pour la consolidation en une dimension de mixtures semi liquides. Dans cette recherche, les méthodes et leurs limites sont détaillées et développées, sont aussi discutées les altérations affectant l'échantillon quand il est transporté de l'appareil de consolidation à la chambre triaxial.

Keywords: Clay, consolidation, saturated materials, stiffness, suction, tunnels.

LIST OF SYMBOLS

CP:	Cell pressure (kPa)
BP:	Back-pressure (kPa)
ESP:	Effective stress path
TSP:	Total stress path
w:	Moisture content (%)
PL:	Plastic limit (%)
LL:	Liquid limit (%)
IL:	Liquidity index defined as $IL = (w - PL)/(LL - PL)$
u:	Pore water pressure (kPa)

σ_v:	Vertical total stress (kPa)
σ_v':	Vertical effective stress (kPa)
$\sigma_{v\,max}'$:	Maximum vertical effective stress (kPa)
σ_r:	Radial total stress (kPa)
σ_r':	Radial effective stress (kPa)
p′:	Mean effective stress invariant defined as $p' = \left(\sigma_v' + \left(2 \cdot \sigma_r'\right)\right)/3$ (kPa)
q:	Deviator or shear stress invariant defined as $q = \sigma_v' - \sigma_r'$ (kPa)
OCR:	Overconsolidation ratio defined as $OCR = \sigma_{v\,max}' / \sigma_v'$
A:	Skempton's A parameter
B:	Skempton's B parameter
K_o:	Coefficient of earth pressure at rest defined as $K_o = \sigma_r' / \sigma_v'$
Cu:	Undrained shear strength (kPa)
Cc:	Compression index
Cs:	Swelling index
e:	Void ratio
α:	Anisotropic stiffness ratio defined as $\alpha = \left(E_h / E_v\right)^{0.5}$
E_v:	Vertical Young's modulus (kPa)
E_h:	Horizontal Young's modulus (kPa)

INTRODUCTION

Underground excavations in urban areas require an estimation of ground movements so that their effect on adjacent structures and services can be evaluated before construction. Typical approaches to investigate the problem range from empirical methods to the use of numerical analyses. The former are more widely used because of their simplicity, but the accuracy of the results is known to be limited. In recent years, improvements in finite element analyses, together with the development of different constitutive models, are allowing a more global approach to the problem. Despite this, it is interesting to note that both research centres and industry generally continue to use the simplest constitutive models. The reason for this is simple: the theory behind the basic models is more widely understood and the parameters required by the more sophisticated models are not easily obtained from conventional in-situ and laboratory testing. The user has to be confident in terms of knowing the application and limitations of the models. Sometimes, the published work is not clear as to whether the constitutive model really gives predictions close to the values observed in-situ, when using the parameters available, or whether there is a tendency to modify these parameters in order to get the expected result.

One of the aims of this research project is to evaluate how appropriate some of the currently available constitutive models are for the study of stress paths created by single and twin tunnels. In order to do this, both numerical analyses and laboratory testing are being undertaken. In this paper only the sample preparation for laboratory testing is discussed.

For the purposes indicated above, and due to the unavailability of natural samples, Speswhite kaolin dry powder has been used in this research for the preparation of reconstituted overconsolidated stiff samples. The fact that using a processed soil would reduce variability and improve repeatability of results for the final analyses was also taken into account. The consolidation device was considered to be of key importance when producing repeatable samples and so special attention was given to the design of an appropriate system. Consolidation procedures used in other universities were reviewed at the beginning of the project, together with the facilities available and K_o-consolidation devices used at Birmingham.

For the present, the consolidation device can be described as containing two different parts: the consolidation chamber and the pressure system. Based on previous experience, a consolidation chamber was built and also a rig frame and pressure system based on the manual application of calibrated weights. This initial consolidation device is called Device A in this paper. A full study of the performance of this equipment was carried out and combined with the observations from the behaviour of the Speswhite kaolin, different proposals were considered for the reconstruction of the geological formation of the soil. These involved either using only a consolidation device or both a consolidation device and a triaxial cell, where the radial strains are kept to zero. From the various options proposed, the most appropriate solution was selected considering all the factors.

Whatever option is used to reproduce the theoretical in-situ stresses, there is always a point during the process when the sample is disturbed and its properties are potentially modified. This occurs when the sample is extruded from the consolidation device to be trimmed and prepared for installation in the triaxial cell. These processes involve changes in the stress state due to the removal of total stresses and mechanical and physical disturbances. A similar process occurs with natural samples during sampling and preparation. Mechanical and physical disturbances can be kept to a minimum, but some are unavoidable. If these disturbances can be considered as not taking place, and the only alteration that the soil experiences is the change in stress path due to the relief of total stresses, the process is considered to be 'perfect'. If however, this 'perfect' process is affected by other factors such as friction during extrusion or drying out during sample preparation, the process is considered 'imperfect'.

This paper contains information on the following aspects of sample preparation:

- The specifications required for this project samples and the reasons for these specifications.
- Previous experiences on the K_o-consolidation of reconstituted samples.
- Consolidation Device A designed for this project, including its performance, limitations and some results.
- Proposed procedures for the complete reproduction of the geological history of the soil and their limitations.
- Variations in p′ as a result of disturbances to which the sample is subjected between its removal from the consolidation device and its arrangement in the triaxial cell.

1. SAMPLE REQUIREMENTS

The samples for this project were required to approximately reproduce the conditions observed in stiff London Clay at a depth of 30m. Anon (1991) gives values for the undrained shear strength (Cu) in the range 50 to 350 kPa (increasing with depth) and for the coefficient of earth pressure at rest (K_o) between 1 and 1.5. For this research, a Cu value between 75 and 150 kPa and a K_o value near 1.5 were chosen.

As the samples were prepared from slurry, they were considered to be saturated after consolidation. Appropriate checks were made, however, in order to verify this.

The computer-controlled stress path cell used in this research can test 38 mm and 50 mm diameter samples. However, because some of the proposed tests require on-sample instrumentation, 50 mm diameter samples were considered more appropriate.

2. PREVIOUS K_o-CONSOLIDATION EXPERIENCES

Many authors have prepared reconstituted samples from slurry for triaxial testing. This involves the process of K_o-consolidation being carried out either completely in an external consolidation device or partially in the consolidation device and partially in the triaxial cell itself. The choice depends on the equipment available, the stress levels and the proposed testing programme. Some of the methods used by other researchers have been identified from the literature and are summarised in Table 1. A quite common procedure consists of consolidating a body of soil with dimensions bigger than those of the triaxial sample and then trimming the sample to an appropriate size (usually 38 mm, 50 mm or 100 mm diameter). Al-Tabbaa (1987) used a quite unusual way of consolidating the slurry in which the consolidation device was set up using parts of the triaxial cell.

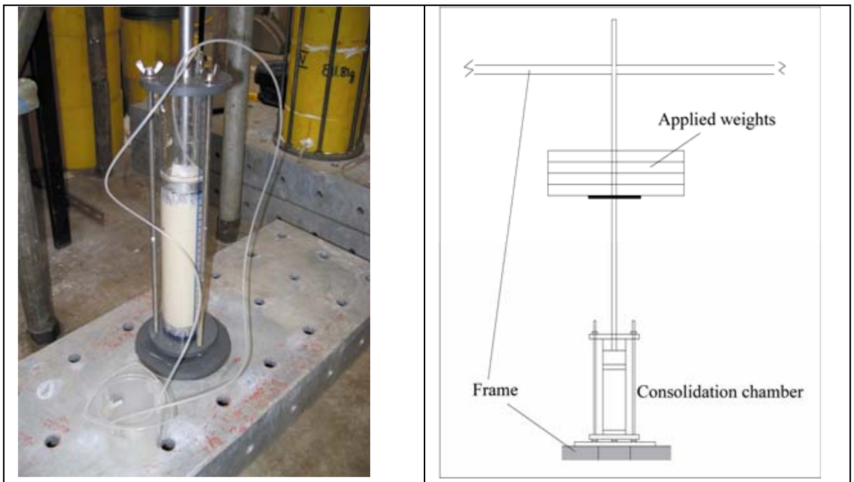
Table 1. Different procedures for the one-dimensional consolidation of reconstituted samples

Author(s)	Description	
1. Jardine, Symes & Burland (1984)	Soil/s used :	Natural North Sea clay
	Sample diameter:	38 mm
	K_o-Consolidation Process:	Partially performed inside the selected consolidation equipment and finalised in the triaxial cell.
	Consolidation device and trimming:	225 mm diameter Oedometer: The samples are consolidated to a σ'_v of 200 kPa and trimmed from the ´cakes´.
	Triaxial equipment:	Hydraulic Stress Path Cell (for samples requiring anisotropic consolidation): Anisotropic consolidation inside the triaxial cell to a final vertical effective stress (σ'_v) equal to 400 kPa and a radial effective stress (σ'_r) of 200 kPa by following a stress path resulting in very small lateral strains. This condition was held for 48 hours and then the stresses were changed to give the desired state of overconsolidation in the samples before being sheared undrained after a further pause of 48 hours.
2. Al-Tabbaa (1987)	Soil/s used :	Processed Speswhite kaolin clay
	Sample diameter:	38 mm
	K_o-Consolidation Process:	Partially performed inside the selected consolidation equipment and finalised in the triaxial cell for some of the samples (for others, isotropic consolidation was used).
	Consolidation device and trimming:	Sample former: The slurry was placed on a former that fits into the triaxial cell in order to use their capabilities including the loading frame. This arrangement (with the sample surrounded by a membrane and with top and bottom filter papers and porous stones) allowed the lower part of the sample to already be fixed for subsequent triaxial testing and only the upper part had to be fixed after trimming and removing the sample former. The slurry was consolidated to a maximum vertical effective stress ($\sigma'_{v\,max}$) of 140 kPa with increments being left for 12 hours. The total load corresponded to a mean effective stress p′ = 111 kPa (using an experimentally obtained value of $K_o = 0.69$). The sample was then unloaded to a σ'_v of 70 kPa to reach an overconsolidation ratio (OCR) equal to 2. This, based on the author's experimental results, left the sample under isotropic conditions ($K_o = 1$), that could then be easily recreated in the triaxial cell.
	Triaxial equipment:	Computer-controled Triaxial cell: The K_o-consolidation process was regained and in some cases with an unloading stage.
3. Atkinson, Charles & Mhach (1990)	Soil/s used :	Various including London clay, Oxford clay and kaolin
	Sample diameter:	38 mm
	K_o-Consolidation Process:	Completely performed in a consolidation cylinder.
	Consolidation device and trimming:	38mm diameter consolidation cylinder: Consolidation of samples (reconstituted from slurry) in order to ensure full saturation up to a pressure enough to allow the samples to be handled. The applied vertical stresses were low only up to 70 kPa.
4. Powrie, Pantelidou & Stallebrass (1998)	Soil/s used :	Processed kaolin clay
	Sample diameter:	38 mm
	K_o-Consolidation Process:	Completely performed inside the selected consolidation equipment and similarly reproduced in the triaxial cell in an attempt to regain the in-situ state and study the sensitivity of the test results to K_o and recent stress history.
	Consolidation device and trimming:	200 mm x 550 mm rectangular press: σ'_v was gradually increased up to 1250 kPa and then unloaded to different values of 150, 332 and 500 kPa. The samples were cored from the clay block using a thin-walled tube and trimmed to the required height.
5. Fearon & Coop (2000)	Soil/s used :	Natural Argille Scagliose (Italy)
	Sample diameter:	Not indicated
	K_o-Consolidation Process:	Completely performed inside a consolidometer, but not much detail is given in the paper.
	Consolidation device and trimming:	Consolidometer: The soil is loaded until the sample can be handled to be put into the triaxial apparatus.
6. Hau (2003)	Soil/s used :	Processed Speswhite kaolin clay
	Sample diameter:	38 mm
	K_o-Consolidation Process:	Completely performed inside the selected consolidation equipment.
	Consolidation device and trimming:	100 mm diameter Oedometer: The oedometer had drainage at the top and bottom. The specimens were subjected to incremental pressure up to 200 kPa, and each increment was held for at least 48 hours. The unloading process went down to 100 kPa which, according to Al-Tabbaa (1987), would leave the sample in an approximately isotropic state of p´ = 100 kPa and so afterwards could be easily recreated in the triaxial cell. The whole process is said to take about three weeks. During extrusion a thin wire was run along the circumference of the sample to reduce friction when pushing out the specimen. Samples were trimmed to the required size using a wire saw and a trimming apparatus.

3. CONSOLIDATION DEVICE A –WEIGHTS BASED

3.1. Description

Different apparatus have been used at Birmingham for the one-dimensional consolidation of soils. In general, each device is designed and built according to the individual researcher's requirements and application. One of the designs, based on the work of Atkinson et al. (1990), for the consolidation of 38mm samples, consisted of a consolidation chamber and a pressure system using dead weights. This equipment was modified and adapted to satisfy the requirements of the current research. The consolidation chamber was kept unchanged, except that the size was increased to 50 mm diameter (Figure 1a). The method of applying the stress however, was modified. A metallic frame was built to hold four vertical rods with horizontal plates attached to support the applied weights. In this way four samples could be prepared at the same time. The general arrangement for a single device is illustrated in Figure 1b.



(a) (b)

Figure 1. Device A: consolidation chamber plus pressure system using dead weights

The main body of the consolidation chamber is formed from an acrylic transparent tube of 50 mm internal diameter held vertically by three horizontal discs and three vertical rods. Using larger diameter tubes and trimming to the required 50 mm diameter samples (with a ratio of length to diameter of 2) was also considered, but there were obvious limitations in terms of the maximum vertical effective stress that could be applied using weights alone. Samples produced from both methods are obviously subject to some disturbance during extrusion and trimming. The length of the transparent acrylic tube was calculated in order to have, at the end of the consolidation process, samples longer than 150 mm whatever the maximum vertical effective stress needed to be applied. This would allow trimming of the sample from the less disturbed central part and using the remaining length for other measurements such as moisture content (w) or Cu as required. An acrylic tube of length 360 mm was found to be appropriate for specimen preparation.

Dial gauges were used for accurate readings of the settlement during consolidation, but the tube had also a scaled tape attached to it for a secondary check.

Drainage was allowed both upwards and downwards by using ballotini plastic balls (2.5 mm diameter), filter papers and metallic meshes at both ends.

Device A was initially checked for general performance mainly in terms of alignment and safety. Afterwards, thirteen samples were carefully prepared, with different characteristics, in order to identify the requirements for reaching the specified soil properties for the project.

3.2 Sample details

As commented, 13 samples were prepared using Device A with the following aims:

- To study repeatability, evaluated in terms of the void ratio (e).
- To find the compression index (Cc) and the swelling index (Cs) parameters of the soil.
- To find the Cu - $\sigma'_{v\,max}$ and Cu - liquidity index (IL) relationships.
- To study the effects of using oil for reducing the tube wall/soil friction.
- To study the effect of using different types of water (tap, de-ionised and de-ionised de-aired).

The samples were prepared using Speswhite kaolin clay from the same batch of material. The liquid limit (LL) and the plastic limit (PL) were determined as 65 % and 33 % respectively. For every sample, the slurry was prepared by mixing 550 g of dry soil with a water content of 1.5 times the LL in a mechanical mixer for 1.5 hours. Moisture contents of between one and two times the LL have been used by other authors:

- Al-Tabbaa (1987) worked with Speswhite kaolin and used a value of w equal to 120 %, which corresponds to about 1.74 times the LL.
- Burland (1990) stated that the slurry should have a water content between the LL and 1.5 times this value.
- Hird & Hajj (1995) used a value of 1.5 times the LL.
- Kim (1996) used an initial water content of about twice the LL.
- Powrie et al. (1998) used a water content of 100 %, but the authors do not specify the LL and PL values of the Speswhite kaolin used.
- Hau (2003) used a water content value of twice the LL.

The prepared mixture was poured into the consolidation tube to an initial height of 295 mm. The initial load applied always corresponded to the weight of the rod plus the piston (equal to 3.18 kg). Every load step was held for 48 hours to ensure full pore water pressure (u) dissipation.

The details for each sample are summarised in Table 2.

Table 2. Sample details

Sample Code	$\sigma_v'_{max}$ (kPa)	Water type	Oil
IN 1.1	301	Tap	-
IN 1.2	450	Tap	-
IN 1.3	620	Tap	-
IN 1.4	770	Tap	-
IN 1.5	1017	Tap	-
IN 1.6	903	Tap	-
IN 1.7	1114	Tap	-
IN 1.8	620	Tap	-
IN 1.9	804	Tap	-
IN 2.1	638	De-ionised	-
IN 2.2	638	Tap	WD-40
IN 2.3	638	De-ionised de-aired	-
IN 2.4 *	638	Tap	-

* This was the only sample that was loaded and then unloaded to the minimum weight of the rod and piston (3.18kg).

3.3. Results

3.3.1. Void ratio – σ_v' relationship

The void ratio change with σ_v' for all the samples is shown in Figure 2. After a stress of about 150 kPa the variability in void ratio is small and only differences of 0.1 are observed for the same stress level. Major differences appear for stresses below 100 kPa. These are considered to be mainly due to friction between piston/tube and rod/frame.

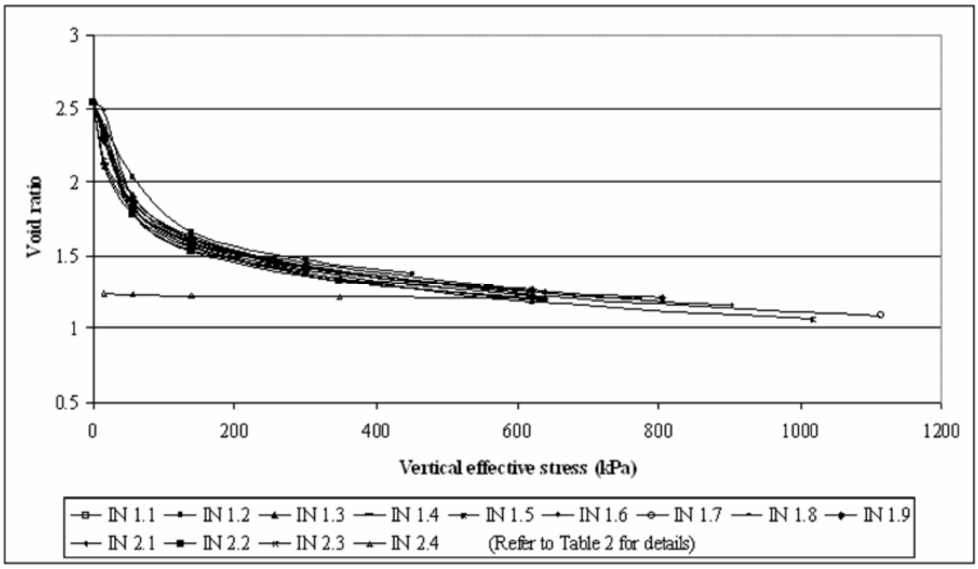


Figure 2. Void ratio changes with σ_v' during the K_o-consolidation of Speswhite kaolin slurry under variable conditions

Previous work at Birmingham has indicated that the use of tap water or de-ionised water does not introduce differences during consolidation unless chemical properties have to be studied. This agrees well with patterns shown in Figure 2. The trend is also not changed if de-aired water is used for the slurry.

For the sample IN 2.2, WD-40 oil was placed on the inside surface of the consolidation tube expecting to obtain beneficial effects. Figure 2 indicates that there is no major variation in the soil behaviour. It was noted that when this type of lubricant was used, the soil and oil mixed together when pouring the slurry into the consolidation tube and the final sample appeared to be more inhomogeneous.

From these results, Cc and Cs were calculated as 0.583 and 0.015 respectively.

3.3.2. Cu – IL relationship

Figure 3 illustrates the results in terms of Cu against IL at the maximum value of vertical effective stress. Cu was measured with a small hand vane during extrusion of the sample. Two or three samples from the remaining soil were taken for an averaged determination of w.

Muir Wood (1990) proposed the following relationship between Cu and IL:

$$C_u = 2 \cdot 100^{(1-IL)} \tag{1}$$

The results from the present experiments can be inconsistent with the expression above because Cu in equation (1) is the remoulded soil strength. However, it was considered of interest to include this relationship for Speswhite kaolin in Figure 3 for comparative purposes. It is noted that there is a similarity between equation (1) and the current results that can be rewritten as

$$C_u = 200 \cdot e^{-4.6052 \cdot IL} \quad (2).$$

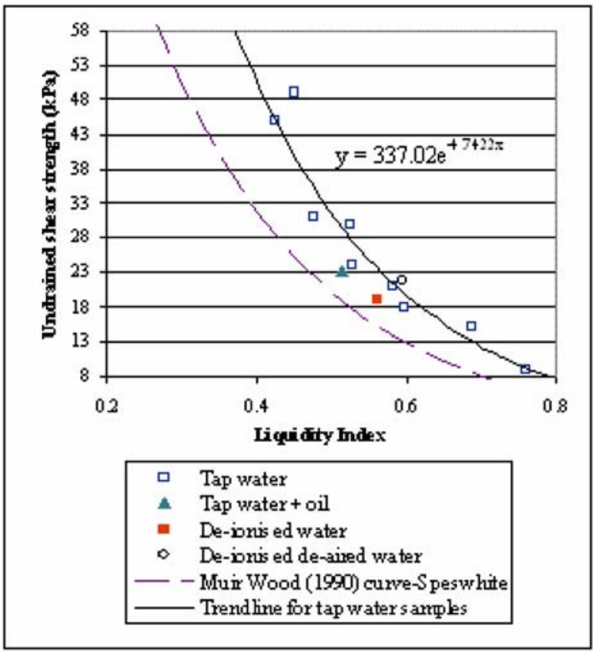


Figure 3. Cu – IL relationship for one-dimensionally consolidated Speswhite kaolin reconstituted specimens with an initial w equal to 1.5 LL

3.3.3. Cu - $\sigma'_{v\,max}$ relationship

Figure 4 illustrates the relationship between Cu, from the hand vane tests, and the maximum applied vertical effective stress. The exponential trend curve was used to define a suitable range of vertical stresses in order to obtain the required strength (Section 1). According to the equation shown in Figure 4, σ_v' should be of at least 1300 kPa, which corresponds to a Cu of about 75 kPa.

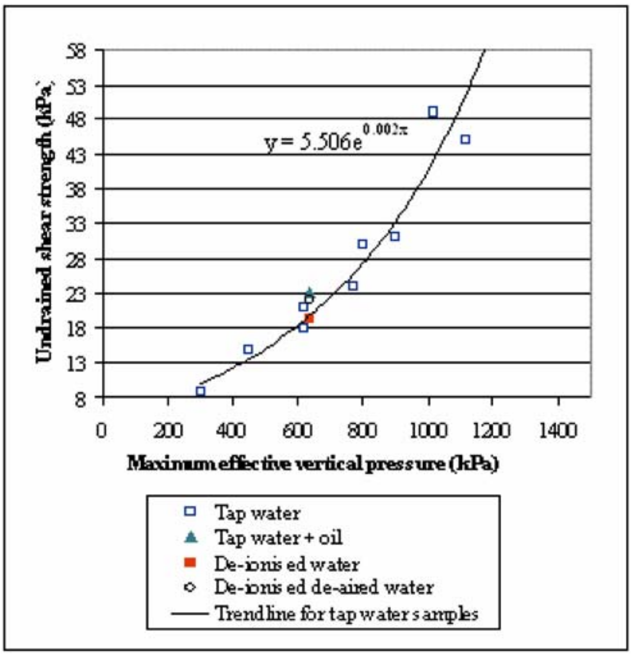


Figure 4. Cu - $\sigma'_{v\ max}$ relationship for one-dimensionally consolidated Speswhite kaolin reconstituted specimens with an initial w equal to 1.5 LL

3.3.4. Tube friction

During consolidation of the slurry, friction between the soil and the walls of the tube occurs. As a result, the clay particles arrange themselves into an internal concave structure. The effect is less noticeable at the top of the specimen, but the soil is clearly anisotropic throughout the sample. Some of the samples were pulled apart and the structure is clearly visible as illustrated in Figure 5.

Figure 5. Concave surfaces created in the soil during one-dimensional consolidation

In order to reduce this effect, and after having tried lubricants with no success (sample IN 2.2), dry PTFE spray was considered as an alternative. However, it was found to be unsuitable since some components in the spray reacted with the acrylic polymer from which the tube was made of. Alternatives are currently being considered.

4. PROPOSALS FOR THE REPRODUCTION OF THE GEOLOGICAL FORMATION OF A NATURAL STIFF SOIL

The objective of preparing K_o-consolidated samples was to reach the required soil state from which to continue additional stress paths related to tunnel excavations. After observing the behaviour of the Speswhite kaolin during consolidation four options were proposed, coded as GH1, GH2, GH3 and GH4 respectively, for the reproduction of the geological history of a natural overconsolidated clay, including deposition and later unloading due to erosion, excavation or similar. The subsequent sections introduce the different proposals, highlight their limitations and indicate the final option chosen.

4.1. Proposal GH1

The first proposal consists of:

- Partial K_o-loading in the consolidation device (from a to b in Figure 6).
- 'Perfect' release of total stresses when the soil is removed from the consolidation device ($\sigma_v = \sigma_r = 0$) leaving the specimen under an isotropic effective stress state with negative pore water pressure (from b to c). The stress path will be within the yielding surface and so generally both q and p′ will decrease.
- Consideration of the effect of an 'imperfect' process, including mechanical and physical disturbances during extrusion, trimming and installation in the triaxial cell (from c to c′; this point is further developed below and in Section 5).
- B-check, saturation (if required), identification of p′ and definition of an appropriate back-pressure (BP) (c′).
- Continuation of the Ko-loading up to the required maximum effective stress, about $\sigma_v' = 1300$ kPa as found in Section 3.3.3 (from c′ to e through d generally not coincident with b).
- K_o-unloading until the required OCR, where $K_o > 1$ (from e to f).

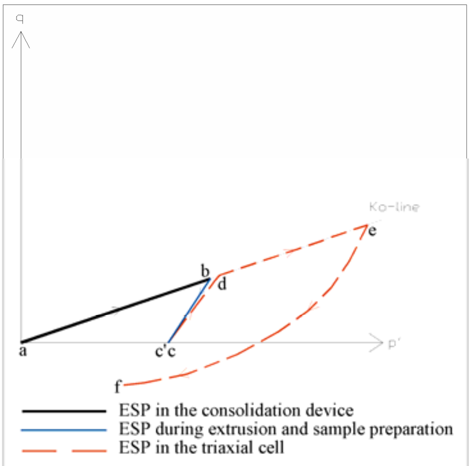


Figure 6. Reproduction of the geological history of a natural soil: Proposal GH1

Limitations:

I. Evaluating the disturbances suffered by the specimen in terms of the difference between c and c′ is not easy since the prediction of the conditions at point c can only be estimated. p′ at point c is commonly estimated by using Skempton (1954) equation:

$$\Delta u = B \cdot [\Delta\sigma_r + A \cdot (\Delta\sigma_v - \Delta\sigma_r)] \quad (3)$$

but this method is not very accurate due to:

- Soil anisotropy.
- Soil non-elasticity.
- A being usually considered equal to 1/3 but in fact it is not a soil constant and depends on the sample OCR and stress path (Atkinson & Bransby 1978).

Some alternatives to Skempton's equation can be found in the literature. Doran et al. (2000) for example, worked with natural clays and presented a method, based on a cross-anisotropic elastic model, for the determination of in-situ stresses requiring measurements of water suctions in the sample and knowledge of the soil stiffness. One of the limitations of the method is the assumption that suction values measured in the sample come from a 'perfect' release of stresses or what is the same, have not been affected by any disturbance during sampling and preparation. The method can have however a better application in this case where from the effective stresses at point b (Figure 6), suctions at point c (and so p′) can be estimated and compared with p′ measured at c′.

II. As the axial and radial strains are measured on samples by means of ±2.5 mm range submersible LVDTs, initial estimation of soil deformations and judgement are required so that the strains induced during one-dimensional consolidation in the triaxial well do not exceed the transducers' range.

III. σ_v' at point b is fixed by the maximum working pressure that could safely be applied to Device A.

IV. Difficulties involved in performing K_o-consolidation in a triaxial cell.

4.2. Proposal GH2

The second proposal consists of:

- K_o-loading in the consolidation device up to the required maximum effective stress $\sigma_v' = 1300$ kPa (from a to b in Figure 7).
- K_o-unloading down to isotropic conditions as previously performed by Al-Tabbaa (1987) (from b to c).
- Consideration of the effect of an ‘imperfect’ process, including mechanical and physical disturbances during extrusion, trimming and installation in the triaxial cell (from c to c′; this point is further developed below and in Section 5).
- B-check, saturation (if required), identification of p′ and definition of an appropriate BP (c′).
- Continuation of the K_o-unloading until the required OCR, where $K_o > 1$ (from c′ to e; this point is further developed below).

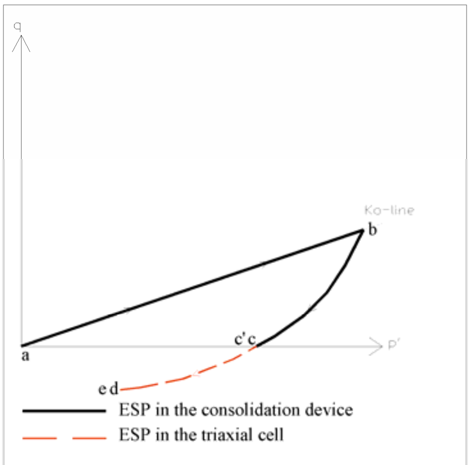


Figure 7. Reproduction of the geological history of a natural soil: Proposal GH2

Limitations:

I. The consolidation Device A does not allow the required maximum vertical effective stress at point b due to safety reasons.
II. The theory behind Al-Tabbaa (1987) approach, with respect to points c and c′ (see Table 1), assumes no mechanical and physical disturbances during extrusion and specimen preparation (‘perfect’ process) in such a way that for $\Delta q = 0$ and $B = 1$ (fully saturated material), Skempton’s equation gives $\Delta u = \Delta\sigma_r$ (equal to Δp for isotropic conditions) and so $c = c'$. Disturbances, however, will make c′ different to c. Due to this, the continuation of the effective stress path (ESP) in the triaxial cell (from c’ to e) can differ from the expected ESP from c to d.
III. Difficulties involved in performing K_o-consolidation in a triaxial cell.

4.3. Proposal GH3

The third proposal consists of:

- Partial K_o-loading in the consolidation device (from a to b in Figure 8).
- K_o-unloading down to isotropic conditions (from b to c).
- Consideration of the effect of an ‘imperfect’ process, including mechanical and physical disturbances during extrusion, trimming and installation in the triaxial cell (from c to c′; this point is further developed in Section 5).
- B-check, saturation (if required), identification of p′ and definition of an appropriate BP (c′).
- Continuation of the K_o-loading up to the required maximum effective stress $\sigma_v' = 1300$ kPa (from c′ to e through d).
- K_o-unloading until the required OCR, where $K_o > 1$ (from e to f).

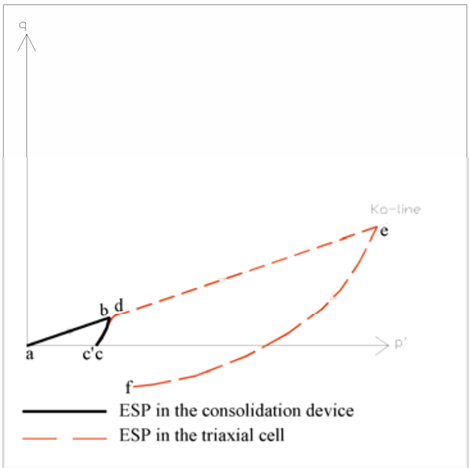


Figure 8. Reproduction of the geological history of a natural soil: Proposal GH3

Limitations:
The limitations in this case are a combination of the ones described for GH1 and GH2 with respect to the disturbances occurring at point c, σ_v' at point b, and the likelihood that the on-sample transducer range will be exceeded during K_o-consolidation in the triaxial cell.

4.4. Proposal GH4

The fourth proposal consists of:

- K_o-loading in the consolidation device up to the required maximum effective stress $\sigma_v' = 1300$ kPa (from a to b in Figure 9).
- K_o-unloading until the required OCR, where $K_o > 1$ (from b to c).
- 'Perfect' release of total stresses when the soil is removed from the consolidation device ($\sigma_v = \sigma_r = 0$) leaving the specimen under an isotropic effective stress state with negative pore water pressure (from c to d). The stress path can have different orientations depending on the soil anisotropic stiffness ratio $\alpha = (E_h / E_v)^{0.5}$ (Doran et al. 2000). For $E_h > E_v$, the stress path is inclined to the left with p′ decreasing.
- Consideration of the effect of an 'imperfect' process, including mechanical and physical disturbances during extrusion, trimming and installation in the triaxial cell (from d to d′; this point is further developed in Section 5).
- B-check, saturation (if required), identification of p′ and definition of an appropriate BP (d′).
- Total stress path to return to point c at the end of the consolidation and definition of an appropriate BP (from d′ to f through point e; this point is further developed below).

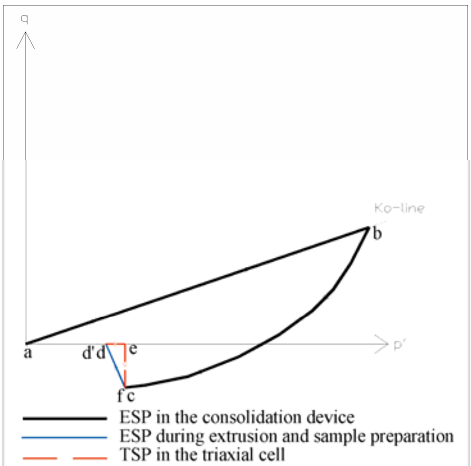


Figure 9. Reproduction of the geological history of a natural soil: Proposal GH4

Limitations:

I. The consolidation Device A does not allow the required maximum vertical effective stress at point b due to safety reasons.
II. Similar considerations to Point I in GH1 for points d and d′.

III. If the K_o-consolidation process is not regained in the triaxial cell, the TSP from d′ to f can modify the behaviour of the sample in terms of its stiffness (Baldi, Hight &Thomas 1988).
IV. Point f might differ from the desired point c due to the performance of the triaxial cell.

4.5. Selection of proposal

From the four GH proposals, and after analysing the different possibilities and implications, GH1 was considered the most convenient for this particular study. Amongst other reasons for the selection, there was the fact that further consolidation helps in getting rid of any likely effects of sample disturbance during extrusion from consolidation Device A on subsequent soil behaviour.

5. VARIATIONS OF p′

Assuming the case where the soil is under an anisotropic stress state at the last moment in the consolidation device, ‘perfect’ release of total stresses will imply changes in q, and therefore also in p′, depending on the soil properties until the pore water pressure reaches equilibrium again. For a clay, which undergoes undrained behaviour, this should not theoretically involve any volume change. As explained above, additional changes in p′ are introduced by means of disturbances applied to the sample during extrusion and preparation for triaxial testing. Depending on the disturbance type and soil state, p′ can be further decreased or increased (Baldi et al. 1988) and some of the factors can give rise to volumetric changes (e.g. those involving water suction). The implications of p′ variations in the case of natural samples have been investigated for example by Hight et al. (1992), who studied the effect of p′ disturbances on the behaviour of a lightly overconsolidated natural clay in terms of strength, stiffness and bounding surfaces changes.

According to Baldi et al. (1988), who reviewed the state-of-the-art in triaxial testing methods, disturbances to p′ can be less severe in the case of stiff clays compared to other soils. However, important variations have been observed during the tests carried out during the current project.

5.1. Sources of disturbance

Baldi et al. (1988) commented on the factors that can potentially take part in the modification of p′ from the value expected after a ‘perfect’ process. These have been classified in Table 3 according to the following groups:
(a) Factors occurring outside the triaxial cell.
(b) Factors occurring inside the triaxial cell.

Table 3. Factors involved in p′ disturbances

Factors Group (a)	Factors Group (b)
Stresses applied to the sample during extrusion, trimming and handling.	Any additional stresses applied during installation in the triaxial cell.
Atmosphere humidity and temperature (sample getting wet or drying out).	Time elapsed between setting up the sample in the triaxial cell and the application of the all-round confining pressure.
Size of the specimen.	Amount of water available by means of the pore pressure and back-pressure lines.
Saturation level of the sample.	Water exchange between specimen and filter papers. Radial filters may introduce water content inhomogeneities.
Storage (if applicable).	Porous stone coarseness. High air entry porous stones have been found to be convenient to facilitate cavitation occurring in these rather than in the pore water pressure and back-pressure lines. The use of high air entry porous stones requires a two port base in order to allow saturation of the stone after de-saturation because of the sample suction.
	Membrane type and state (soaked or unsoaked). Soaked membranes do not absorb water from the sample but care must be taken if the specimen has high negative pore pressures in which case it is the soil absorbing water from the membrane.

CONCLUSIONS

This paper has presented a detailed overview of some of the issues surrounding the preparation of soil samples for triaxial testing, including the devices for consolidating samples from a slurry. These issues are particularly important when trying to create samples with a known stress history (for example stiff overconsolidated clay samples) to allow subsequent specific stress paths to be followed. The issue of sample disturbance due to the transfer from a consolidation device to the triaxial equipment is also particularly important and is discussed in this paper. Although extensive laboratory triaxial and stress path testing have been carried out around the world on samples prepared from a slurry, the details relating to sample preparation are often poorly described and the impact on the subsequent test results not clearly stated. This paper has attempted to collect some of the previous experiences reported in the literature and combine this with the experiences from a current research project, where stress path testing related to the soil behaviour around tunnels is of particular interest.

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