Experimental and numerical studies on the mechanical behaviour of two quasi saturated fine soils

Etude expérimentale et numérique du comportement mécanique de deux sols fins quasi saturés

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ABSTRACT: A large number of triaxial undrained tests on remoulded clay and on remoulded silt are analysed. It is shown that the degree of saturation is never perfectly obtained and that the unsaturated state has a significant effect on the stress and strain paths. Considerations on the fluid compressibility, based on the backpressure level and the presence of air bubbles, allow proposing a constitutive model dedicated to quasi-saturated soils. This model is used for the numerical simulation a series of triaxial tests with various initial saturation degrees and backpressures. The simulation results help to explain the large scatter observed in the test results.

RÉSUMÉ: Une grande quantité d'essais triaxiaux non drainés réalisés sur une argile remaniée et sur un limon remanié a été analysée. Il apparaît que la saturation totale n'est jamais complètement atteinte et que le manque de la saturation a une influence significative sur la courbe contrainte – déformation. La prise en compte de la compressibilité du fluide en fonction du niveau de la contre-pression et présence de bulles d'air permet de proposer un modèle constitutif pour les sols quasi saturés. Ce modèle a été utilisé pour la simulation d'une série d'essais triaxiaux avec différents degrés de saturation initiaux et contre-pressions. Les résultats de la simulation permettent d'expliquer l'importante dispersion des résultats d'essai qui est observée.

1 INTRODUCTION

The interpretation of oedometer and triaxial tests is usually based on the hypothese that the soil specimens are fully saturated and the experimental procedures are established in order to fulfil this basic requirement. However, as it will be shown in this paper, full saturation is very difficult to obtain in effect.

In particular, it is shown that the use of a backpressure during the saturation phase of the specimens can significantly improve the saturation level. However, reaching perfect saturation often requires a considerable time, which, in most cases, largely exceeds the duration of the tests. Practically, this means that perfect saturation of the specimens is very difficult to reach. The influence of this slight lack of saturation on the mechanical behaviour is mainly due to the higher compressibility of the pore water containing air bubbles. From the point of view of experimental results, this increase of the compressibility of pore fluid will be reflected on the stress-strain curves, on the stress paths in the p'-q plane, etc... So, the interpretation of classical experimental results is, in fact, really delicate.

More importantly, the numerical simulations, achieved with the constitutive model, has to take into account the higher compressibility of the fluid phase, depending on the evolving degree of saturation.

This paper comprises two parts. The first part will be devoted to a new analysis of some classical tests on two Belgian fine soils (Kruibeke clay and Gembloux silt), performed in a frame of corporation research contract, taking account of the fact that the soil samples may be only quasi saturated. The second part shows how to account for this lack of saturation into the numerical simulation. Some simulation results will be presented.

Five partners, named as *Lab A*, *Lab B*, ... *Lab E* hereafter, have participated in the experimental program.

2 DESCRIPTION OF THE STUDIED SOIL SAMPLES

The main physical characteristics of the remoulded test samples, averaged upon the total measurements by 3 laboratories, are summarised in table 1. It is seen that the full saturation of the clay samples is not reached at all, the silt samples seem to be better saturated than the clay samples. However, these obtained values should be viewed with caution: the degree of saturation is not directly measured but is the result of a calculation sensitive to small variations of some parameters. It can be shown that a slight error on measurement of sample volume or on the value of γ_s (the density of soil particles) may bring about an important error on the calculated saturation (Li 1999). So, in all likelihood, the studied samples are not full saturated.

Table 1. Main physical characteristics of test samples

	Dry volumetric weight γ_d (kN/m^3)	Water content w (%)	Saturation degree S_{rw} (%)
Clay samples	13.28	33.46	89.6
Silt samples	16.63	22.52	102.2

3 EXPERIMENTAL RESULTS

The experimental program comprises essentially oedometer and triaxial tests. All the experimental results can be found in Bolle et al. (1995). In this paper, only the most significant ones are presented.

The oedometer tests give the elastic and plastic slopes of the compressibility curve κ and λ. All related results obtained by the different laboratories are consistent and lead to the average elastoplastic characteristics of samples summarised in table 2 (obtained with an average void ratio e = 0.99 for clay, 0.58 for silt).

Table 2. Elastoplastic characteristics of test samples

Clay	Loading slope λ		0.153
	Unloading slope κ^*	σ_v=2000 kPa	0.098
		σ_v=100 kPa	0.040
Silt	Loading slope λ		0.055
	Unloading slope κ^*	σ_v=2000 kPa	0.002
		σ_v=200 kPa	0.006

* The unloading slope varies with the compression stress. The values are calculated for the beginning and the end of unloading.

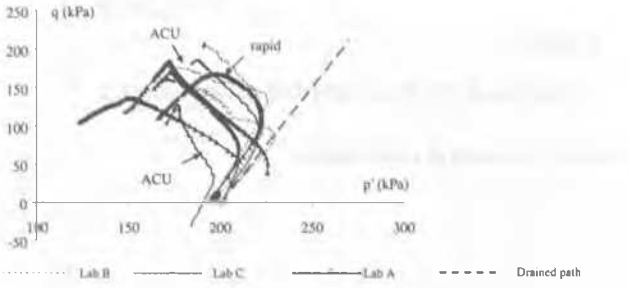

Figure 1. Results of triaxial tests on Kruibeke clay (σ_c = 200 kPa OCR = 1)

Table 3. The cohesion and internal friction angles of tests samples

	Clay samples		Silt samples	
	ϕ_c (°)	c (kPa)	ϕ_c (°)	c (kPa)
OCR = 1	14-22	16-34	25-31	7-15
OCR = 2	20-21	12-24	25-35	2-15
OCR = 4	23-24	9-17	25-31	7-16

The triaxial tests allow determining some basic shearing parameters of soil such as internal friction angle ϕ_c, cohesion c, critical state line (CSL), contractancy or dilatancy. The results are generally presented in a p'-q plane where p' is the mean effective stress and q the deviatoric stress.

Numerous CU triaxial tests were performed with different preconsolidation pressures and OCR states. For brevity, only a few typical results for clay are given here as an example (Fig. 1). The results of Gembloux silt will not be reported. It is worth recalling that some tests were repeated with some variants in the test procedure. These are indicated on the corresponding figures: *ACU* means anisotropic consolidation, *rapid* means the tests with higher loading velocity.

The main trends for both clay and silt are presented briefly here:

- The Lab C's results show less contractancy for normal consolidated behaviour and more dilatancy for over consolidated behaviour than that of Lab B and Lab A
- The higher the σ_c, the higher the contractancy
- The stress paths follow always the drained path at first before *turning to the left* as expected for an undrained soil
- The dispersion of the results is very important in such a way that the specific tests (ACU tests, etc...) cannot be distinguished.

The characteristics of critical state are summarised in the table 3 hereafter. Both cohesion and internal friction angle measurements reflect a large dispersion.

4 DETAILED ANALYSES OF THE EXPERIMENTAL RESULTS

The dispersion of the obtained experimental results has been put in evidence. Certainly, the causes of this dispersion are numerous and it is very difficult to discern between them. However, some attempts are made to clarify certain important aspects.

The soil mechanical behaviour is directly affected by the pore pressure variations. Under undrained conditions, the interstitial pressure generation followed by an external loading depends essentially on the relative compressibility of the soil and of the pore fluids (pore water or pore air or the air-water mixture). The later one is controlled essentially by the saturation.

Within a certain range of saturation, both the air phase and water phase are continuous. In such cases, the pore water pressure is different from the pore air pressure, their variation is not equal neither: suction exists. The soils in such range of saturation are considered as *unsaturated* soils.

It has been postulated that there exists a critical saturation beyond which the air becomes occluded in the form of bubbles. In such cases, it is said that the soils are in *quasi-saturated* state.

Summarily, the variation of the interstitial pressure resulting from an external loading under undrained conditions is a very complex phenomenon. Our studies will be limited to the *quasi-saturated* case.

4.1 *Saturation state in soil samples (researches on back-pressure approach)*

For saturating a soil specimen, a very common technique is to apply a backpressure to the pore water as in our project:

- At both Lab B and Lab A, a backpressure u_0 = 100 kPa is applied with de-aired water. The total duration of the application of backpressure is 24 hours at Lab B, only 1 hour at Lab A.
- At Lab C, the backpressure u_0 = 100 kPa is applied but with non de-aired water.

Under a backpressure, the water is forced into the soil specimens, the pore air volume in the specimen decreases by compression in accordance with Boyle's law and by dissolution into the pore water in accordance with Henry's law. As a result, the saturation degree increases (Fredlund et al. 1993).

4.1.1 *The backpressure required for achieving the full saturation*

For a given initial saturation S_{rw0}, the backpressure required for achieving the full saturation (u_{100}) depends on the use of the de-aired or non de-aired water (Li 1999).

In the case of using de-aired water, it can be obtained by:

$$u_{100} = \bar{u}_{a0} \frac{(1-S_{rw0})(1-h)}{h} \qquad (1)$$

where h is the Henry's volumetric coefficient of solubility (h = 0.02 at 21 °C for air dissolved in water).

The non de-aired water is in principle saturated with dissolved air and contains likely air bubbles. In such case, u_{100} is much more important:

$$u_{100} = \bar{u}_{a0} \frac{1-S_{rw0}}{hS_{rw0}} + \frac{x(1-S_{rw0})}{h(1+S_{rw0}x)} \frac{(1-S_{rw0}+hS_{rw0})}{hS_{rw0}} \bar{u}_{a0} \qquad (2)$$

where $\bar{u}_{a0}$ refers to the initial absolute pressure and x represents the fraction of the air bubbles introduced into the sample with the non de-aired water (noting that $x=0$ means that the water contains dissolved air, but no air bubbles).

The influence of the presence of air bubbles in the water is shown on the figure 2 (non de-aired water case is drawn with x = 0, 0.01, 0.05, 1). For a specimen with an initial saturation of 90 %, the backpressure required for reaching the complete saturation would be 500 kPa for de-aired water, 600 kPa for water with 1% air and 650 kPa for water with 2% air.

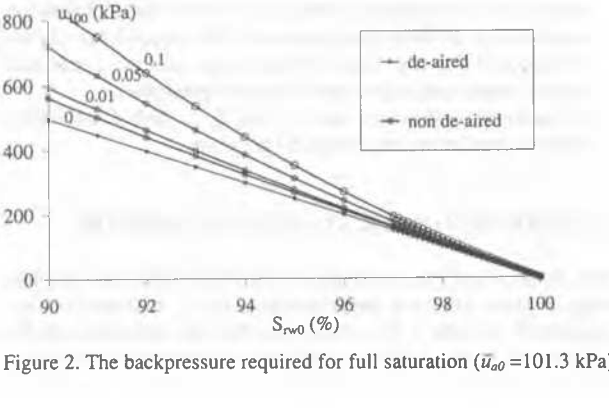

Figure 2. The backpressure required for full saturation ($\bar{u}_{a0}$ =101.3 kPa)

4.1.2 *Time required to increase the degree of saturation*

The above development on the backpressure was made without taking into account one fact: the air compression is almost instantaneous, while the air dissolution into water needs time. From the theoretical and experimental studies carried out by Black et al. (1973), the time required for full saturation can be calculated by (figure 3):

$$t_{100}=\left\{\frac{1}{\alpha}\left[\frac{1-S_{rw0}}{1+49R\left(1-S_{rw0}\right)}\right]\right\}^{1/b} \tag{3}$$

where α and b depend on the saturation and $R=u_0/u_{100}$ represents the relative level of the applied backpressure.

According to these results, the necessary time to saturate a sample may be very long: it needs one week to saturate completely a sample with an initial degree of saturation around 98% under a backpressure of $u_0 \approx 100$ kPa$\approx u_{100}$ ($R=1$). For a sample with an initial saturation of 95%, the time necessary for full saturation is about 600 days under a backpressure $u_0 \approx 100$ kPa (it equivalents $R \approx 0.4$). It is unrealisable.

The above analysis permits to reach a conclusion that, with the procedure adopted by any laboratory (a back pressure about 100 kPa and one day in maximum for stabilisation), the saturation of the test specimens can't be perfect. In most cases, it ranges from 92 to 96 % before shearing phase. In Lab C where the samples are likely to be better saturated (initial saturation seems to be higher than that in other laboratories), the applied backpressure could hardly ameliorate the saturation state due to the use of non de-aired water.

4.2 *Compressibility of air-water mixture*

The analyses thereon have demonstrated that the soil samples are, in fact, only partially saturated or, say, quasi-saturated.

As stated before, the mechanical behaviour depends on the generation of pore fluid pressure that is controlled essentially by the compressibility of air-water mixture χ_f, which, in turn, is strongly depending on the saturation degree. It follows (figure 4):

$$\chi_f = S_{rw}\chi_w + (1-S_{rw}+hS_{rw})\chi_a \tag{4}$$

where χ_w is the water compressibility. For pure de-aired water, at 20°C and under a pressure of 100 kPa, $\chi_w = 4.58*10^{-7}$ kPa^{-1}. χ_a refers to the air compressibility ($=1/\bar{u}_a$ where $\bar{u}_a$ is the absolute air pressure).

One important aspect can be remarked from the figure 4: when the saturation is close to 100 %, a slight de-saturation (even 1 or 2 % less) could increase greatly the compressibility of pore fluid. As a result, it influences strongly the variation of the water pressure generation when the sample is subjected to an external load, and so the undrained stress paths in the plane (p'-q). This explains to a great extent why the stress paths in the plane (p'-q) didn't *turn to the left* as expected for a saturated soil: it is because the samples didn't reach the saturation at all! And

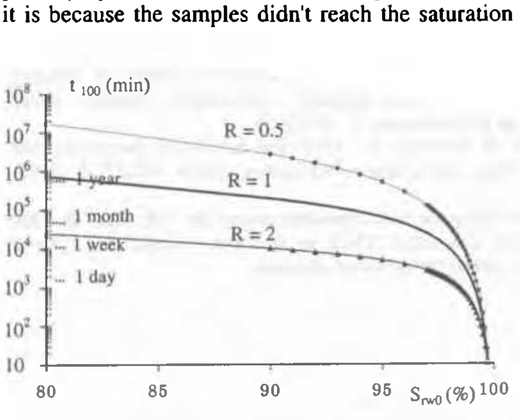

Figure 3: Time to saturate a specimen using backpressure

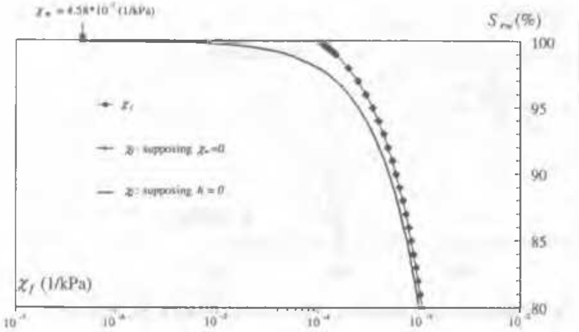

Figure 4: Compressibility of air-water mixture (u_a =100 kPa)

the pore fluid is far away from being incompressible as supposed frequently!

5 CONSTITUTIVE MODELLING FOR THE HYDRO-MECHANICAL BEHAVIOUR OF QUASI-SATURATED SOILS

As stated before, the compressibility of pore fluid increases significantly when there is a slight lack of saturation in the samples. As a result, from the point of view of constitutive modelling, this aspect should be taken into account.

5.1 *Mechanical aspects*

The mechanical behaviour of a soil is usually described using a constitutive law. Numerous experimental and numerical studies have postulated that the effective stress concept is still suitable for quasi-saturated soils on condition to take into account the pore fluid compressibility correctly (Chang & Duncan, 1983, Fleureau & Indarto, 1993). In other words, the quasi-saturated soils can be viewed as a two-phase system: a solid phase and a much more compressible fluid phase. Then, any proposed saturated soil constitutive law could theoretically be apt to describe the mechanical behaviour in the quasi-saturated state.

5.2 *Hydraulic aspects*

Taking into account the influence of the deficiency of the saturation into the numerical simulation implies some developments in the pore fluid flow law: the higher compressibility of pore fluid changes greatly the evolution of the storage law.

The storage law describes the evolution of the mass of the fluid stored in a unit volume. In the case of a quasi-saturated soil, it is similar to that of a fully saturated soil:

$$\dot{S} = \rho_f n \dot{u}_f \chi_f = \rho_f n \dot{u}_w \chi_f \tag{5}$$

Both χ_f and ρ_f (density of the pore fluid) depend on the saturation. Here we assume $u_f = u_w = u_a$.

The variation of the saturation with the pore pressure should be defined. It can be described by (Li 1999):

$$S_{rw} = \frac{\left(\bar{u}_{a0}+\Delta u_w\right)S_{rw0}}{\bar{u}_{a0}+\Delta u_w S_{rw0}(1-h)} \tag{6}$$

6 NUMERICAL SIMULATION OF TRIAXIAL ELEMENTARY TESTS

Some numerical results with the accents on the influence of the insufficiency of the saturation will be shown. The constitutive law used is the Cam clay model.

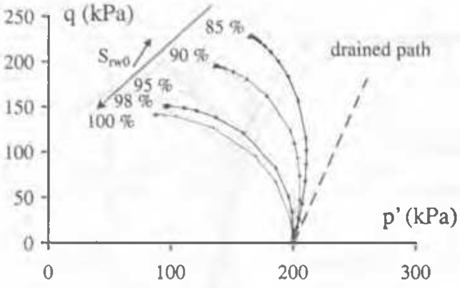

Figure 5. Effects of the saturation degree (σ_c=200 kPa, OCR = 1)

The influences of the lack of saturation and pf the backpressure level are put in evidence as shown in figure 5-6.

The comparison between the numerical simulations and experimental results is uneasy since the latter ones present a large dispersion. Some qualitative comparisons have been made nevertheless, as illustrated in the figure 7. The simulation results are obtained with a backpressure of 100 kPa like in the experimental tests. The mechanical parameters are chosen from the table 2 and 3.

For the Kruibeke clay, the experimental results correspond to the numerical ones with a very low saturation, about 80-85 %. This confirms what we have observed before: the clay samples are far away from fully saturated. Their average measured saturation degrees were about 90% ± 5% (cf. §2).

For the Gembloux silt, the experimental results of Lab C correspond to the simulation results with an initial saturation S_{rw0} around 85 %, while the Lab A and Lab B results correspond to

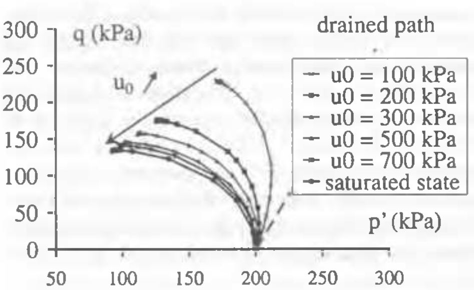

Figure 6. Effects of backpressure (OCR=1, σ_c=200 kPa, S_{rw0}=85%)

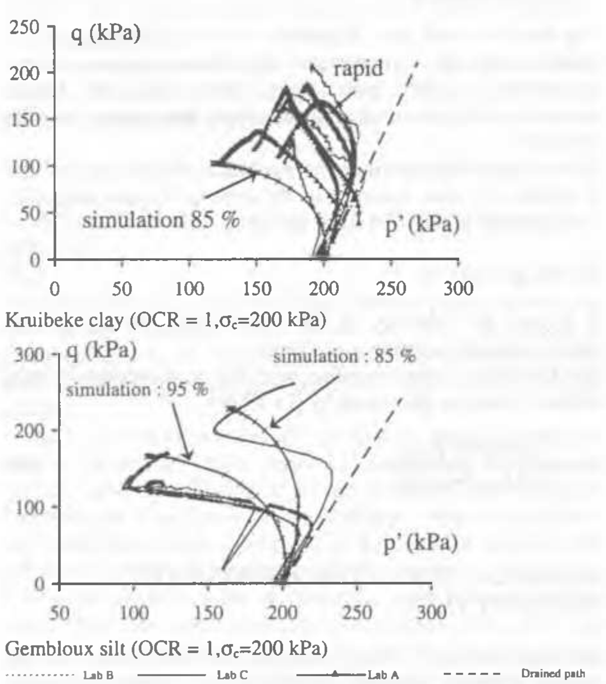

Figure 7: Comparisons with the experimental results

the numerical ones obtained with S_{rw0}> 95 %. Remember that the measured initial saturation of the silt is about 100% ± 3% (cf. §2). The numerical simulation confirms that the state of saturation in the silt is much better than that of the clay.

7 CONCLUSIONS

The interpretation and analysis of the experimental results allow quantitatively characterising the behaviour of these materials: elastic and elastoplastic parameters, dilatancy, contractancy... However, the significant scatter of the test results stimulates to scrutinise the causes of such scatter, starting with a detailed comparison of the experimental procedures. This study has led to a precise definition of a quasi-saturated state. It has also allowed evaluating qualitatively and quantitatively how different aspects of the test procedures influence the response of the specimens and the quality of experimental results on quasi-saturated soils.

In particular, it is shown that the use of a backpressure during the saturation phase of the specimens can significantly improve the saturation degree. However, to reach perfect saturation often requires considerable time duration and pressure level, which, in most cases, largely exceed the practical conditions of the tests. Practically, this means that a perfect saturation of the specimens is very difficult to reach.

However, this slight lack of saturation significantly increases the compressibility of the fluid (a mixture of water and air) contained in the pores. A constitutive model of the fluid compressibility has been proposed which takes into account the initial saturation degree, the backpressure level, and the amount of air bubbles. Associated to classical constitutive models and to the Terzaghi postulate, it allows to accurately simulate numerically the undrained triaxial tests and to explain some apparent scatter between experimental results.

One concludes then that the fluid compressibility largely influences the test results and must be considered for their analysis in terms of any constitutive model. Moreover, such quasi saturation state should be taken into account in any geostructure modelling, when short time is considered with respect to the permeability level.

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