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STRESS RELIEF DISTURBANCE AND RESIDUAL PORE PRESSURE IN COHESIVE SOILS

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ABSTRACT

Sampling induces structural modifications in clay which depend on the stress and strain paths followed during sampling history. A complete description of disturbance is very difficult, because it originates in situ during drilling and is completed in the laboratory with reloading at the pre-existing stress conditions.

In this paper, only the effects of undrained relief of confining effective stresses are investigated for reconstituted natural clays of varying plasticity. During undrained stress relief, negative pore pressure (suction) occurs; this residual stress was selected as a reference parameter for disturbance appraisal and compared with initial conditions before unloading.

For the same type of soil, consolidation was carried out in various stress conditions (isotropic and anisotropic), and both normally consolidated and overconsolidated specimens were made. After undrained unloading, residual stress was evaluated by means of a controlled swelling technique using a modified oedometer and a triaxial device. This method was validated by comparisons with suction plate measurements performed on reconstituted kaolin clay specimens.

Experiments showed various causes of loss of suction in samples, related to plasticity index, stress history, stress conditions and released stress level. For normally consolidated non-structured clays, undrained stress relief gives rise to some important disturbance processes, more evident for anisotropically consolidated samples.

Residual stress may be considered meaningful for stress relief disturbance appraisal.

Key words: cohesive soil, laboratory tests, residual stress, sample disturbance, stress relief, suction (**IGC:** C6/D5)

INTRODUCTION

The mechanical behaviour of saturated cohesive soils is characterised by considerable anelasticity, so that various stress paths between the same initial and final conditions may produce different responses, depending on a number of aspects such as soil structure and rheology, stress history and test conditions. For this reason, it is important to verify the modifications caused in soil by sampling history, before any mechanical test is performed in the laboratory. Disturbance accounts for all the undesired physical processes which arise during sample withdrawal (*drilling* and *coring*), management (*transport* and *storage*), handling (*extrusion*, *trimming* and *mounting*) and, lastly, *recompression*.

Sampling disturbance may be regarded as the result of a compression-extension strain path and an unloading-reloading stress path. The former is related to tube-sampler penetration during coring (*mechanical disturbance*); the latter accounts for stress variations during extrusion from the tube-sampler and subsequent recompression to in situ stress conditions (*stress disturbance*). According to currently used sampling and testing procedures, *stress disturbance* is unavoidable, whereas *machanical disturbance* may be minimised by using large-diameter samplers with low friction, so that little soil is displaced and stressed by tube-sampler penetration. Lastly, disturbance due to *transport*, *storage*, *trimming* and *mounting* may be reduced if expert personnel are available.

Mechanical disturbance has been investigated both theoretically (Baligh et al., 1987) and experimentally (Barden and McGown, 1973; Carrubba, 1989; Chandler et al., 1992). Only empirical studies have been carried out on *transport*, *storage*, *trimming* and *mounting* disturbances (La Rochelle et al., 1986; Atkinson et al., 1992; Hight et al., 1992).

Stress disturbance has received much attention in the last few decades, both theoretically and experimentally (Ladd and Lambe, 1963; Skempton and Sowa, 1963; Kirkpatrick and Khan, 1984; Nakase et al., 1985). It may be subdivided into two phases: *perfect sampling* (Ladd and Lambe, 1963) accounts for stress relief when an *ideal* sample (Nakase et al., 1985) is completely unloaded under undrained conditions. In this case, full extrusion

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from the tube-sampler is required in order to obtain the so-called *perfect* sample (Ladd and Lambe, 1963). *Recompression* is the inverse process, during which the original in situ stress conditions are re-established under drained or undrained conditions (Bjerrum, 1973; Ladd and Foot, 1974; Holtz et al., 1986; Graham and Lau, 1988; Clayton et al., 1992). This stage is required in several tests to evaluate compressibility, deformability and shear strength.

During stress relief interactions among soil skeleton, pore water and surrounding air give rise to negative pore water pressure (*suction*), which may be used as a quality parameter for sampling disturbance when compared to theoretical values or in situ stress conditions.

The change from *ideal* to *perfect* sample is examined in this paper. Tests were carried out on reconstituted natural clays with a wide plasticity range, from non-plastic to highly plastic. For the same type of soil, consolidation tests were performed in varying stress conditions (isotropic and anisotropic), and both normally consolidated and overconsolidated *ideal* specimens were reconstituted. After undrained unloading, the residual stress of *perfect* samples was evaluated by means of a controlled swelling technique using a modified oedometer and a triaxial device. Final suction values were compared with the reference stress level for disturbance appraisal.

STRESS RELIEF DISTURBANCE AND RESIDUAL PORE PRESSURE

Sampling requires soil transfer from the site to the tube-sampler while the existing effective stress conditions remain unchanged. From a practical point of view, existing stress cannot be fully preserved: some variations are induced by drilling, coring and sample retrieval, and by the absence of vertical soil confinement in the tube-sampler. As soon as the sample is extruded in the laboratory, the remaining confining stress vanishes and the soil skeleton swells in order to reach a new equilibrium. In the absence of any surrounding water supply, swelling is prevented by surface tension arising at the water-air interface. During this process, meniscus curvature decreases in proportion to the prevented expansion, and matrix suction develops. According to the principle of effective stress, this negative pore pressure acts as an effective confining stress and may reach very high values if capillary conditions are preserved in the pore space; if cavitation occurs, soil suction is reduced in time.

Following Ladd and Lambe (1963), residual pore pressure may be evaluated by means of the equation:

$$U_R = -\sigma_v' [K_0 + A_{US}(1 - K_0)] \tag{1}$$

where σ_v' is the effective in situ vertical stress, K_0 the at-rest earth pressure coefficient, and A_{US} a Skempton parameter for the undrained unloading of in situ deviator stress. The above approach is valid for saturated cohesive soils with no cementing or sensitivity, in which no pore water cavitation is expected. Parameter A_{US} may vary between 0.1 and 0.4, whereas K_0 is related to the overconsolidation ratio (*OCR*); values of residual stress close to horizontal or vertical in situ effective stresses are expected in normally consolidated or overconsolidated clays respectively.

Laboratory measurements of residual stress provide information on sampling quality compared with theoretical values: differences may be due to high mechanical disturbance during withdrawal, swelling during storage in the presence of drilling fluid, or pore fluid cavitation during extrusion. In these cases, soil samples may be decompressed until they soften.

Residual stress measurement in cohesive soils has received much attention in past decades (Lambe, 1961), but many difficulties are still found in full direct measurement of high negative pore pressure; in fact, negative pore pressure higher than one atmosphere can only be reached in the capillary condition. Indirect measurements are carried out by checking some physical soil processes (Croney and Coleman, 1960; Skempton, 1961; Chandler and Gutierrez, 1986; Fredlund and Wong, 1989). Almost-direct measurement techniques use a pressure differential between pore water and the surrounding air, in order to maintain unchanged the curvature of the pore-water menisci by means of positive air pressure, thus measuring soil suction in a positive pressure field (Chen, 1988).

In general, total suction results from two components: *osmotic suction* and *matrix suction* (Fredlund and Rahardjo, 1993). The former represents free water energy associated with osmotic pressure in the soil-water system; the latter is free water energy associated with the potential capillary rise of water in the soil pore space. In this case, the process is due to surface tension at the air-water interface. As osmotic suction is fairly constant, significant changes in total suction come from changes in matrix suction (Chen, 1988).

SELECTION OF SOIL SAMPLES FOR LABORATORY TESTING

Laboratory testing was performed on four remoulded natural cohesive soils sampled in the Venetian plain Table 1 shows the USCS classification, together with

Table 1. Geotechnical properties of remoulded natural soils

Soil	USCS	G_S	W_L (%)	W_P (%)	PI	C_C	C_S
Organic Clay	OH	2.30	128	53	75	1.60	0.260
Silty Clay	MH	2.65	65	30	25	0.55	0.085
Clayey Silt	CL	2.70	36	25	11	0.40	0.048
Sandy Silt	ML	2.72	30	24	6	0.30	0.026

Note
USCS = Unified soil classification system
G_S = Specific gravity of solids
W_L = Liquid limit
W_P = Plastic limit
PI = Plasticity index
C_C = Compression index
C_S = Swelling index

Atterberg limits (W_L, W_P), plasticity index (PI) and specific gravity of solids (G_S). As may be noted, PI is typical of non-plastic to highly plastic soils. Samples were remoulded to a slurry condition by adding distilled water up to a water content of nearly $1.5 W_L$. The slurry was placed in an oedometer and a triaxial device, to carry out anisotropic and isotropic consolidations; typical compression (C_C) and swelling (C_S) indexes, obtained from the conventional oedometer, are also shown in Table 1.

Results must be interpreted bearing in mind that these samples no longer have their own structure resulting from sedimentation and ageing; however, the aim of the experiment was to highlight the influence of some important geotechnical parameters on final suction. Time effects and void size distribution on suction were not investigated here in detail; for a simplified approach, the plasticity index was selected as reference parameter, since it is inversely proportional to particle size distributions in fine-grained soils.

LABORATORY PROCEDURES FOR SUCTION MEASUREMENTS

Current almost-direct procedures for suction measurements evaluate negative pore pressure well below one atmosphere. A pressure differential is created between soil pore water and the atmosphere (Chen, 1988), acting directly on air (*Pressure Plate*) or on both air and water (*Axis Translation Technique*). No water is allowed to flow in either procedure, and a semipermeable membrane is used to maintain air pressure at a value higher than one atmosphere. However, these procedures are difficult to use when drained and undrained stress paths must be associated with suction measurements, because total stress cannot be changed.

The procedure employed here allowed total stress to be varied over a generic stress path and soil suction to be evaluated by checking sample swelling. Consolidation and swelling in saturated cohesive soils is related to outward or inward water flow through the sample. During undrained unloading, zero total stress is established and water supply neglected, so that swelling is supported by residual stress. After the sample has been connected to an external water supply and total stress changed until no water is flowing through the sample, total stress balances the system, residual stress disappears, and suction is assumed to be the same as equilibrium total stress.

Slurry samples were placed in a modified oedometer or a triaxial device, according to the stress conditions to be applied. In the triaxial cell, samples were confined by the rubber membrane, cap and pedestal; isotropic stress was applied by means of the pressure cell. In the oedometer, samples were confined by the fixed ring, loading plate and basement, and all gaps were sealed in order to avoid any water supply to samples. The standard dimensions of 70 mm in diameter and 20 mm in thickness were employed for the oedometer ring, to minimise friction between soil and ring. Depending on the at-rest earth pressure coefficient, an anisotropic stress state was attained during consolidation. For both oedometer and triaxial apparatus, drainage was only permitted through a very small porous element, with a low air entry value, connected to a pair of ducts.

The whole operation for suction measurements in isotropic and anisotropic consolidated samples is shown in Figs. 1 and 2. During consolidation, the water ducts were connected to a graduated burette for sample volume measurement (Figs. 1a), 2a)). After consolidation, the water remaining in the drainage system was expelled by means of low-pressure air circulation inside the ducts (Figs. 1b), 2b)). Operations were facilitated by the low air entry value and the small size of the porous element. At this point, the sample, in equilibrium with the consolidation pressure, received no water supply from the external environment. Subsequently, as soon as undrained relief of effective stress was carried out (Figs. 1c), 2c)) suction occurred. For suction measurements, a burette was connected to one duct, while the other was left open; confining pressure, close to the anticipated values of residual stress and therefore lower than consolidation stress, was applied to the sample and the drainage system was saturated (Figs. 1d), 2d)). Then the open duct was closed while a reference line was assumed on the burette filled with water (Figs. 1e), 2e)) to carry out measures of the relative change of specimen volume versus confining pressure. This reference line coincided with the fixed water level in the burette. Operations related to both drainage saturation and the fixing of the reference water line, had to be performed quickly in order to avoid absorption or expulsion of water from the sample in the time elapsing before the reference line was ready. In the holding stage, water flow was controlled by operating on total stress (Figs. 1f), 2f)): total stress was increased or decreased if absorption or expulsion of water, respectively, was observed. When the water level in the burette coincided with the reference line and remained steady in time, applied total stress could be regarded as equal to residual pore pressure.

The accuracy of the method is mainly related to swelling index C_S of the soil skeleton and sample size. If the sample does not swell, no matrix suction develops and no absorption of water may be observed. For this reason, the method can be applied only to swelling saturated clays, and the accuracy of measures is improved by the sensitivity of the burette, that is, scale graduation with which any variation of volume can be observed; for commercial burettes with 20 *divisions per* cm^3 an accuracy of about ± 10 kPa was obtained in the measurement of residual stress. In the case of very low swelling indexes, the accuracy of measurement may be lost, unless larger specimens are employed to ensure that a significant volume of water flows through the drainage system.

The method allowed measurements which were accurate and stable in time for both low and high suctions. However, no long-term behaviour was investigated in this research, and suction measurements refer to an equal standing time of samples in the apparatus. In this way, the data are comparable, although some cavitation and

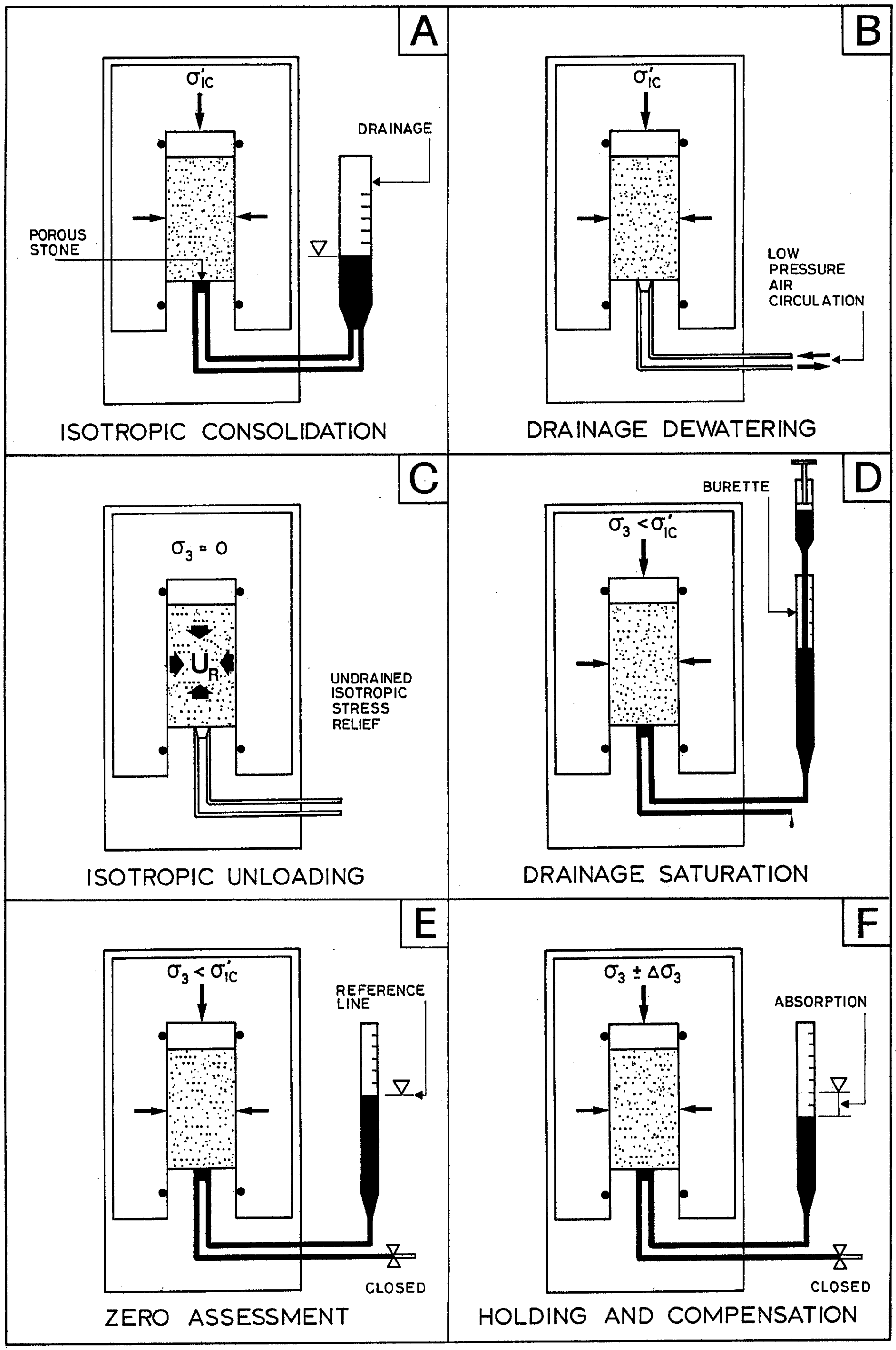

Fig. 1. Procedures for suction measurement in isotropically consolidated samples by means of modified triaxial cell

creep phenomena might have occurred in time.

STRESS PATHS FOLLOWED DURING LABORATORY TESTING

The effect of stress conditions on final suction values was investigated by carrying out isotropic and anisotropic (K_0) consolidations on both normally consolidated and overconsolidated samples. In the latter case, stress history effects were taken into account in terms of the overconsolidation ratio (*OCR*). Stress conditions, stress level and overconsolidation ratio were changed in a regular manner for each soil sample.

Typical stress paths performed on normally consolidated soils are shown in Fig. 3, with reference to the Lambe $t=(\sigma_1-\sigma_3)/2$, $s'=(\sigma'_1+\sigma'_3)/2$ and e-log σ' planes. Complete stress relief was carried out starting from current consolidation stress level, σ'_{vc} in the anisotropic case (Figs. 3a), c)) or σ'_{Ic} in the isotropic case (Figs. 3b), c)).

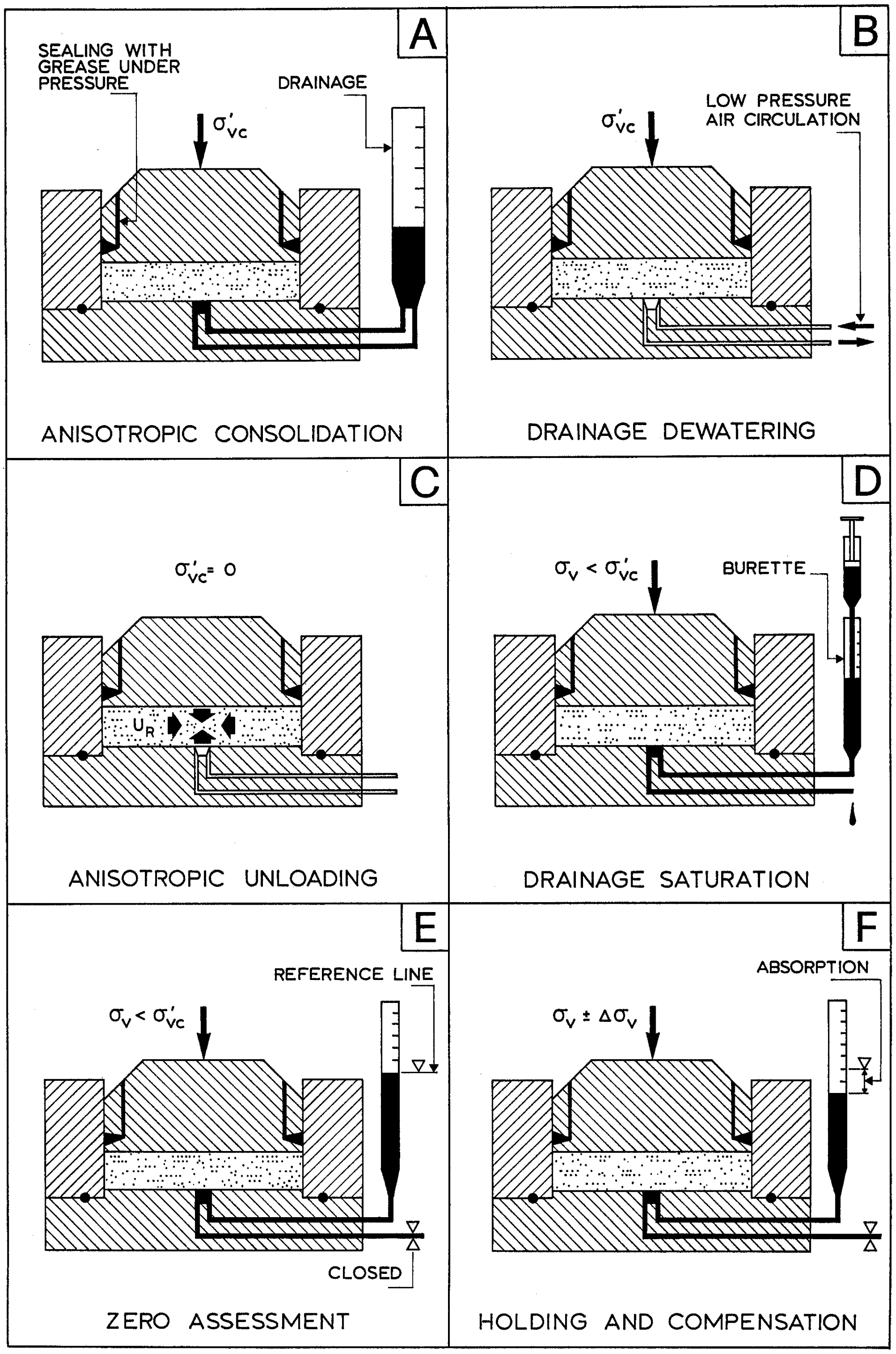

Fig. 2. Procedures for suction measurement in anisotropically consolidated samples by means of modified oedometer

Typical stress paths of overconsolidated soils are shown in Fig. 4, again with reference to planes t-s′ and e-log σ'. When anisotropic consolidation was completed under σ'_{vc} (Figs. 4a), c)), drained unloading was carried out until vertical stress σ'_v. At this stage, the *OCR* was σ'_{vc}/σ'_v. Subsequently, undrained stress relief was performed starting from confining vertical stress σ'_v. Similarly, when isotropic consolidation was completed under σ'_{ic} (Figs. 4b), c)), drained unloading was carried out until confining isotropic stress σ'_i; at this stage *OCR* was σ'_{ic}/σ'_i. Subsequently, undrained stress relief was performed starting from confining stress σ'_i. For both normally consolidated and overconsolidated samples, residual stress U_R corresponded to the total recompression stress under which the void index begins to decrease and water to drain.

In normally consolidated samples, residual stress was compared to consolidation pressures σ'_{vc} or σ'_{ic} reached before undrained unloading (Fig. 3c)). In overconsolidated samples, the reference stress was assumed to be

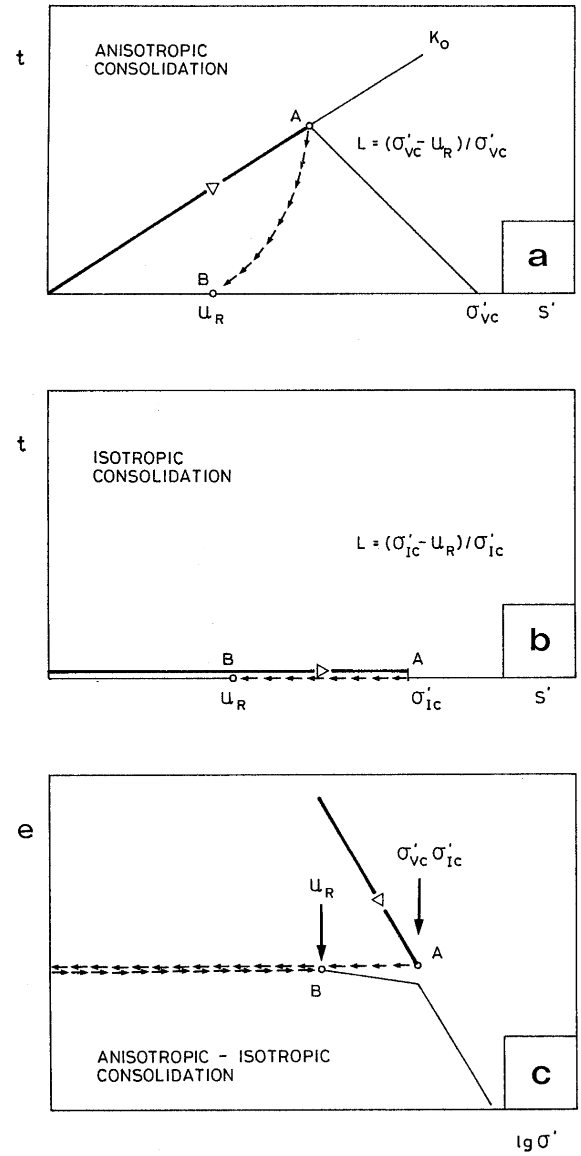

Fig. 3. Typical stress paths performed in normally consolidated soils

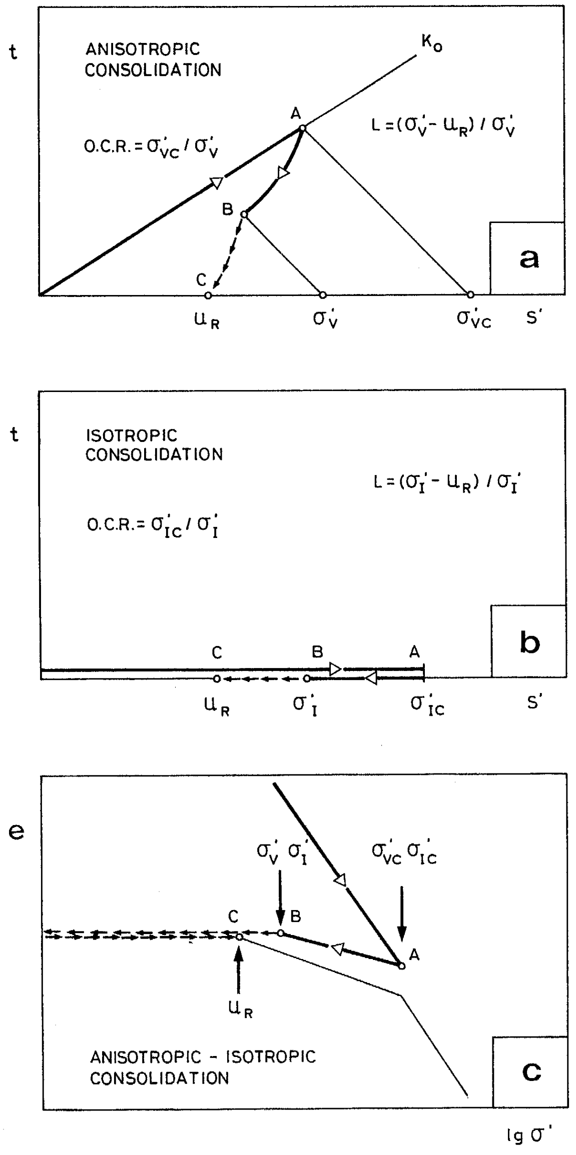

Fig. 4. Typical stress paths performed in overconsolidated soils

equal to confinement stresses σ'_v or σ'_I reached before undrained unloading (Fig. 4c)). A comparison parameter L was introduced, according to the following expression:

$$L=\frac{\sigma'_{vc}-U_R}{\sigma'_{vc}} \tag{2}$$

for normally consolidated samples in anisotropic stress conditions;

$$L=\frac{\sigma'_{Ic}-U_R}{\sigma'_{Ic}} \tag{3}$$

for normally consolidated samples in isotropic stress conditions;

$$L=\frac{\sigma'_v-U_R}{\sigma'_v} \tag{4}$$

for overconsolidated samples in anisotropic stress conditions;

$$L=\frac{\sigma'_I-U_R}{\sigma'_I} \tag{5}$$

for overconsolidated samples in isotropic stress conditions.

Assuming that effective stress before undrained unloading may be fully changed into residual stress, parameter L represents a suction loss with respect to an ideal condition. Depending on stress conditions, stress level and overconsolidation ratio, the amount of suction loss was evaluated for each type of soil.

The influence of various load cycles on suction was not investigated in detail in this paper. However, as long as the swelling index does not change with either consolidation stress level or number of cycles, the presence of cyclic consolidation may involve a quasi-preconsolidation effect, because of more sustained creep.

COMPARISON OF PROPOSED METHOD WITH SUCTION PLATE RESULTS

Comparisons were made between residual stresses obtained by the controlled swelling technique in the triaxial device and by the suction plate method (*Richard plate*). Commercial kaolin clay with plasticity index $PI=30$, liquid limit $W_L=67\%$, and specific weight of solids $G_S=2.63$ was used.

Suction measurements with the triaxial cell were performed on normally consolidated specimens under isotropic pressures of 50, 100, 200, 400 and 800 kPa. After complete undrained unloading, measured suction values were respectively 45, 80, 160, 320 and 640 kPa, with a loss of stress (L) of 10% ~ 20%, depending on consolidation pressures (Fig. 5).

Other isotropically consolidated specimens of kaolin clay were reconstituted in the triaxial cell under the same isotropic consolidation pressures and then unloaded in undrained conditions. The samples were then removed from the triaxial cell and placed inside the suction plate chamber.

The essential components of a pressure plate (Chen, 1988; Fredlund and Rahardjo, 1993) are an air pressure chamber, a semipermeable membrane, and a drainage line. Specimens are placed inside the pressure chamber, which is separated from the drainage line by means of a semipermeable membrane. This membrane consists of a fine ceramic stone or cellulose material having a high air entry, which allows the movement of water but not of air, so that the air and water phase can be controlled separately. After placing the specimens in the chamber, air pressure is applied to increase positive or decrease negative pore water pressure without loss of air or loss of control of the volume of water entering or leaving the specimen. Water is forced out of the soil if air pressure is sufficient to cause positive pore water pressure, whereas it is imbibed into the soil if pore water pressure is negative. The air pressure which causes no flow of water in or out of the specimen is denoted as soil suction.

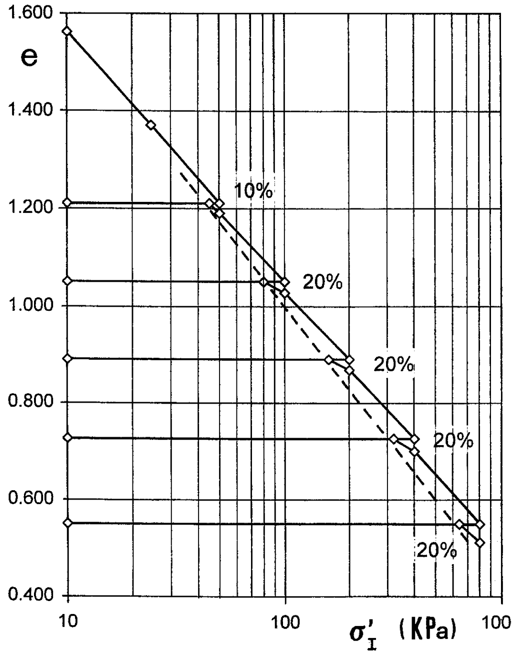

Fig. 5. Suction evaluation in normally consolidated kaolin clay by means of modified triaxial cell

Two procedures were followed with the suction plate method. One is based on monitoring the *dripping point*, which consists of raising the air pressure inside the chamber until initial emission of pore water is observed; at this point, air pressure balances sample suction. However, this method, suitable for non-swelling soils, becomes imprecise in swelling soils because of water absorption from the saturated plate when the air pressure in the chamber is lower than the suction value.

To overcome this difficulty, a second approach was followed, requiring determination of the *retention curve* for samples with different consolidation pressures. Once a specimen has been placed in contact with the saturated plate, it is free to absorb or lose water until equilibrium is reached under a selected value of air pressure (U_{air}) in the chamber. By varying the air pressure and measuring the corresponding water content at equilibrium (W_{eq}), the relationship between water content and the associated air pressure (*retention curve*) was obtained for the isotropically consolidated clay samples. Suction corresponds to the air pressure at which the water content is the same as that of the *perfect* sample. Retention curves were constructed by means of suction plate tests performed on 35 *perfect* samples. The samples were removed from the pressure chamber only at the end of the test, to evaluate the equilibrium water content corresponding to a given air pressure. *Retention curves* are shown in Fig. 6 in non-dimensional form with respect to water content, by dividing equilibrium water content (W_{eq}) by initial water content (W_0) of the *perfect* samples. In this way, intersections of the line $W_{eq}/W_0=1$ with the *retention curves* provide the soil suction values at the various consolidation pressures. The same data are shown again in Fig. 7 in a fully normalised form, also by dividing air pressure values (U_{air}) by consolidation stress (σ_{Ic}). In this case, the line $W_{eq}/W_0=1$ intersects the retention curves at U_{air}/σ_{Ic} values ranging between 0.8 and 1.0 depending on consoli-

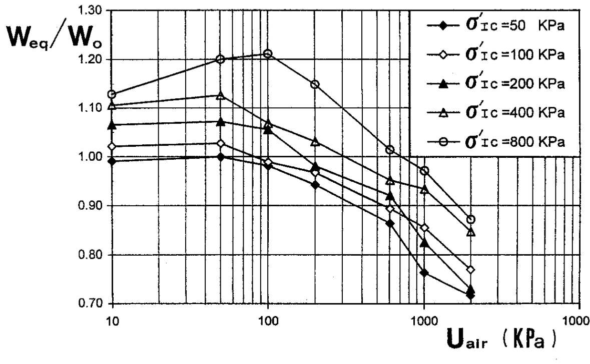

Fig. 6. Retention curves for normally consolidated kaolin clay obtained with suction plate: normalisation with respect to initial water content

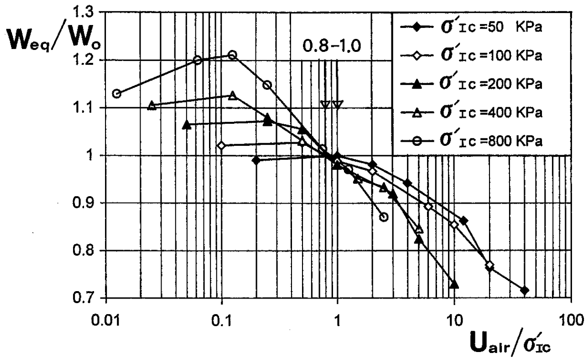

Fig. 7. Retention curves for normally consolidated kaolin clay obtained with suction plate: normalisation with respect to initial water content and consolidation pressure

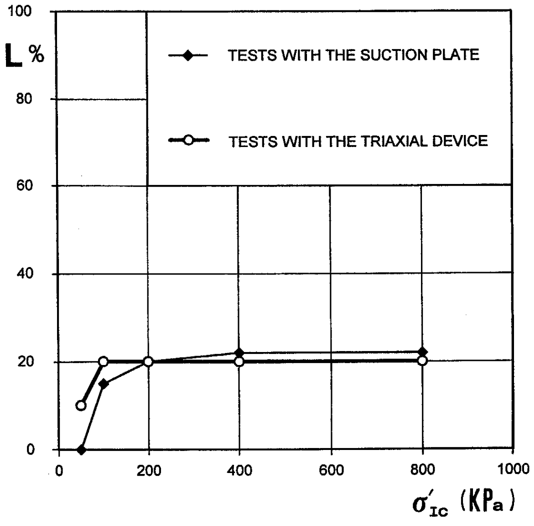

Fig. 8. Comparison between suctions of normally consolidated kaolin clay obtained with modified triaxial cell and suction plate

dation stress level; this means that, in the suction plate method, a maximum suction loss of about 20% is expected for homogeneous kaolin clay. The values of suction loss obtained with both triaxial device and pressure plate are compared in Fig. 8. A good fit is observed, especially for consolidation stresses exceeding 200 kPa.

STRESS PATHS AND RESIDUAL PORE PRESSURE MEASUREMENTS

Following the laboratory procedures proposed above, residual stress was measured for both normally consolidated and overconsolidated soils.

The stress paths related to normally consolidated soils are shown in Figs. 9 and 10 respectively for isotropic (triaxial) and anisotropic (oedometer) consolidations. In this case, the influences of stress level, stress conditions and plasticity index on suction were analysed. Results indicated that residual stress in the samples gradually increased in proportion to the consolidation pressure. The loss of suction was fairly constant with respect to the stress level achieved with isotropic consolidation (Fig. 9). However, in the case of anisotropic consolidation, a more sustained loss of suction became evident as the consolidation stress level increased (Fig. 10). All suction measurements related to normally consolidated soils are shown in Fig. 11: the dependence of L on plasticity index and consolidation stress level is significant in anisotropically consolidated specimens (Fig. 11a)); in the case of isotropic consolidation, only the dependence on plasticity index is evident (Fig. 11b)).

The stress paths related to overconsolidated samples are shown in Figs. 12 and 13, for isotropic and anisotropic stress conditions respectively. Tests were carried out by changing the overconsolidation ratio in a discrete manner, between 2 and 16, so that the dependence of suction on stress level, stress conditions, stress history and plasticity index could be investigated. As may be seen, residual stress increases with confining stress σ'_v or σ'_i, whereas it decreases with the *OCR* in both anisotropic and isotropic stress conditions. For overconsolidated specimens, all measured suction losses are shown in Fig. 14: in general, lower L values were expected with respect to the normally consolidated case. For heavily overconsolidated soils ($OCR \geq 4$), the maximum suction loss was about 20%, regardless of plasticity index or stress conditions during consolidation. For slightly overconsolidated soils ($OCR < 4$), larger suction losses were undergone by the less plastic soils consolidated in anisotropic conditions. The overconsolidation process allows an overall improvement in the elastic response to stress relief disturbance.

LOSS OF SUCTION AND CHANGE IN UNDRAINED STRENGTH

Within the framework of critical state soil mechanics, Wood (1990) has shown that the undrained strength of overconsolidated clay is related to the undrained strength of the normally consolidated state by means of the following relation:

$$\left.\frac{C_u}{\sigma'}\right|_{OC}=\left.\frac{C_u}{\sigma'_{vc}}\right|_{NC}\left(\frac{n}{n_p}\right)n_p^{\Lambda} \qquad (6)$$

in which:

$\left.\frac{C_u}{\sigma'}\right|_{OC}$ = undrained strength of overconsolidated clay normalised with respect to current vertical effective stress;

$\left.\frac{C_u}{\sigma'_{vc}}\right|_{NC}$ = undrained strength of normally consolidated clay normalised with respect to vertical preconsolidation effective stress;

$n=\frac{\sigma'_{vc}}{\sigma'}$ = overconsolidation ratio in terms of vertical stress related to one-dimensional normal compression;

$n_p=\frac{p'_c}{p'}$ = isotropic overconsolidation ratio in terms of mean effective stress;

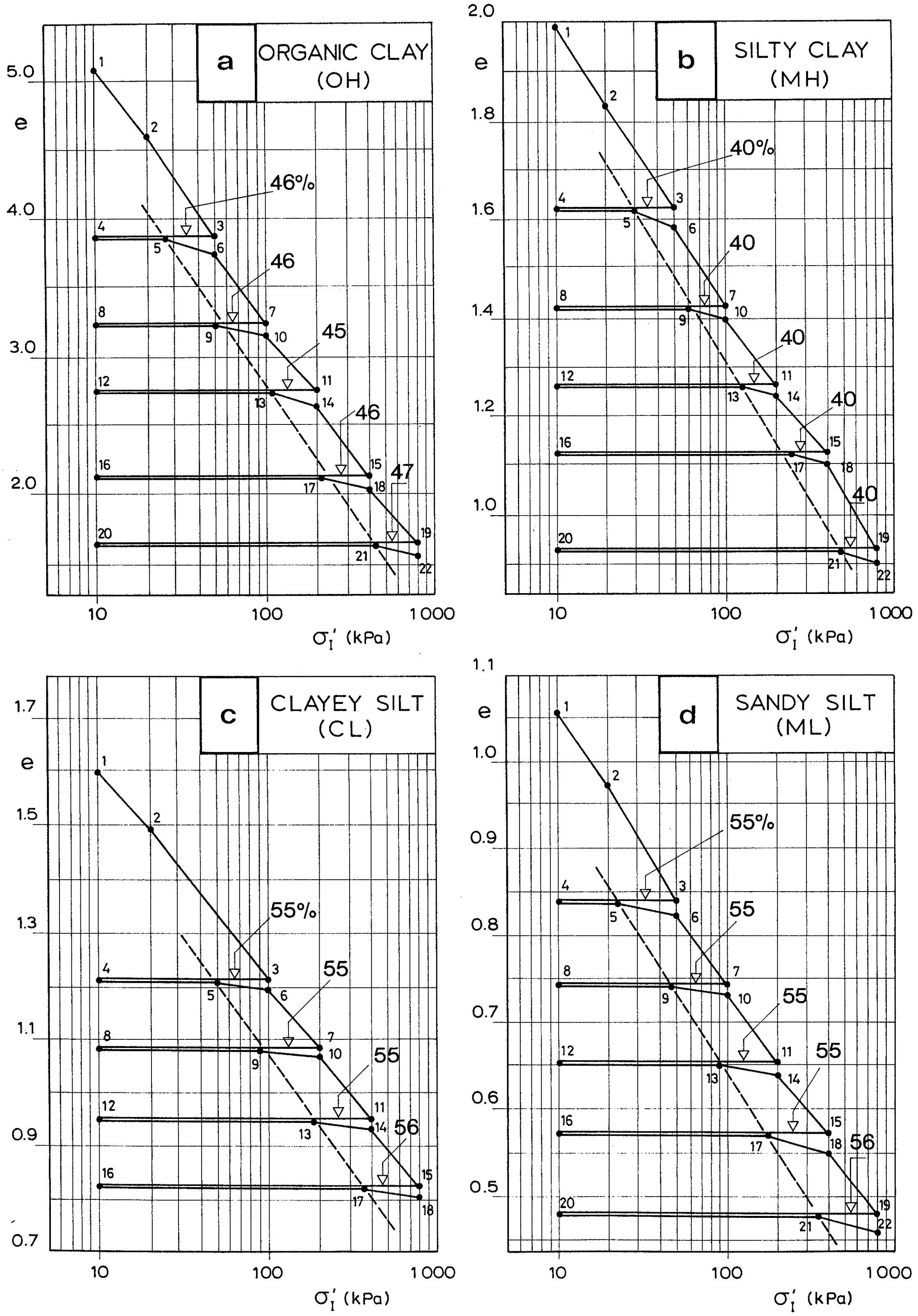

Fig. 9. Suction measurements in normally consolidated soils by means of modified triaxial cell

$\Lambda=\frac{\lambda-\kappa}{\lambda}\cong\frac{C_C-C_S}{C_C}$ = Cam-Clay parameter describing the relative slopes of normal compression (λ) and unloading-reloading (κ) lines for the soil.

For practical purposes, Eq. (6) may be written in the following form:

$$\left.\frac{C_u}{\sigma'}\right|_{OC}=\left.\frac{C_u}{\sigma'_{vc}}\right|_{NC} n^{\mu} \qquad (7)$$

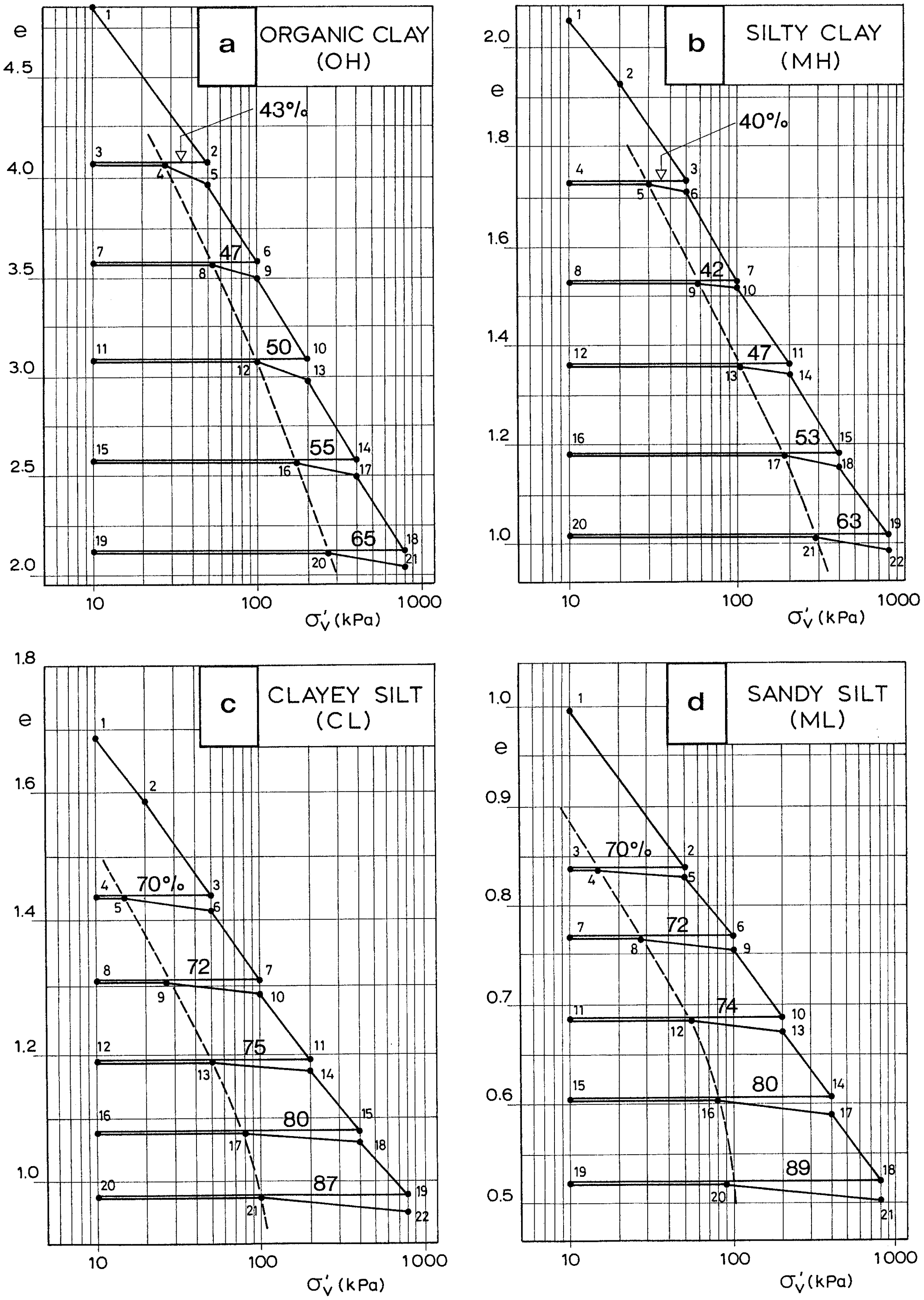

Fig. 10. Suction measurements in normally consolidated soils by means of modified oedometer

Ladd et al. (1977) remark that parameter μ has a mean value of 0.80, but that it falls from 0.85 to 0.75 with increasing overconsolidation.

Any loss of suction increases the overconsolidation ratio of the sample because of the decrease of the current effective stress with respect to the maximum past stress.

Normally consolidated clays which undergo a loss of suction L reach an overconsolidation ratio:

$$n=\frac{\sigma'_{vc}}{U_R} \tag{8}$$

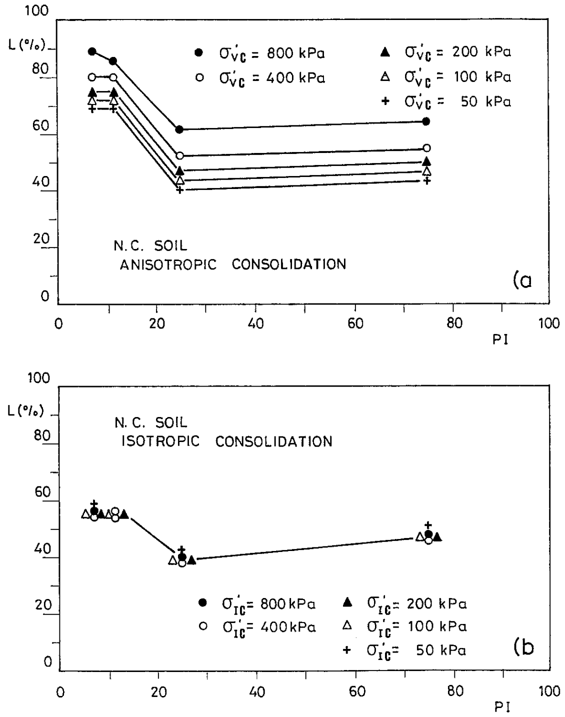

Fig. 11. Loss of suction in normally consolidated soils: a) modified oedometer, b) modified triaxial cell

in which current vertical stress attains isotropic residual stress:

$$\sigma' = U_R \tag{9}$$

and, from Eq. (2):

$$U_R = \sigma'_{vc}(1 - L) \tag{10}$$

Introducing Eqs. (8), (9) and (10) into Eq. (7), the following expression is obtained:

$$\left.\frac{C_u}{U_R}\right|_{OC} = \left.\frac{C_u}{\sigma'_{vc}}\right|_{NC} \left(\frac{1}{1-L}\right)^{\mu} \tag{11}$$

that is:

$$(C_u)_{Disturbed} = (C_u)_{NC,Undisturbed}(1-L)^{1-\mu} \tag{12}$$

For example, for $\mu = 0.80$ and for a maximum loss of suction $L = 90\%$ ($\sigma'_{vc} = 800$ kPa and $PI = 6$ in Fig. 11a)), the disturbed value of C_u is about 63% of the undisturbed value before undrained unloading. For a minimum loss of suction of about $L = 40\%$ ($\sigma'_{vc} = 50$ kPa and $PI = 25$ in Fig. 11a)), the disturbed value of C_u is about 90% of the undisturbed value before undrained unloading. Obviously, for a loss of suction of 0%, the disturbed undrained strength approaches the undisturbed value related to the normally consolidated condition before undrained unloading.

In the case of overconsolidated samples, the nominal overconsolidation ratio is:

$$OCR = \frac{\sigma'_{vc}}{\sigma'_v} \tag{13}$$

where σ'_v is vertical effective stress reached in drained unloading.

The correspondence between undrained strength of normally consolidated and overconsolidated conditions may be put in the form:

$$\left.\frac{C_u}{\sigma'_v}\right|_{OC} = \left.\frac{C_u}{\sigma'_{vc}}\right|_{NC} OCR^{\mu} \tag{14}$$

from which the following expression is obtained:

$$(C_u)_{OC} = (C_u)_{NC}\, OCR^{\mu-1} \tag{15}$$

After undrained unloading, the final overconsolidation ratio is:

$$n = \frac{\sigma'_{vc}}{U_R} \tag{16}$$

and, from Eq. (4):

$$U_R = \sigma'_v(1 - L) \tag{17}$$

Substituting Eqs. (9), (13), (16) and (17) into Eq. (7), the following expression is obtained:

$$\left.\frac{C_u}{U_R}\right|_{OC} = \left.\frac{C_u}{\sigma'_{vc}}\right|_{NC} \left(\frac{OCR}{1-L}\right)^{\mu} \tag{18}$$

from which:

$$(C_u)_{Disturbed} = (C_u)_{NC,Undisturbed} \left(\frac{OCR}{1-L}\right)^{\mu-1} \tag{19}$$

and, from Eq. (15):

$$(C_u)_{Disturbed} = (C_u)_{OC,Undisturbed}(1-L)^{1-\mu} \tag{20}$$

For example, for $\mu = 0.80$ and maximum loss of suction $L = 60\%$ ($OCR = 2$ and $PI = 6$ in Fig. 14a), the disturbed value of C_u is about 83% of the undisturbed value before undrained unloading; for a minimum loss of suction of about $L = 10\%$ ($OCR = 16$ and $PI = 25$ in Fig. 14a)), the disturbed value of C_u is about 98% of the undisturbed value related to the overconsolidated condition before undrained unloading.

MAIN CAUSES OF REDUCTION OF SOIL SUCTION

Measurements indicate that reduction of suction only increases with stress level in anisotropically consolidated clays, whereas it is constant in normally consolidated clays. This may be related to shear strains which develop in anisotropically consolidated specimens during undrained unloading: changing stress conditions from anisotropic to isotropic produces appreciable axial extension, especially in normally consolidated clays, together with some radial contraction. For example, undrained unloading of about 800 kPa, starting from the normal consolidation condition, gives rise to an axial extension strain (ε_v) varying between 0.75% and 9% depending on soil nature (Fig. 15). This shear strain, without volumetric strain, may induce considerable relative displacements between soil particles and some variation in pore size. The influence of friction at the soil-ring interface in the

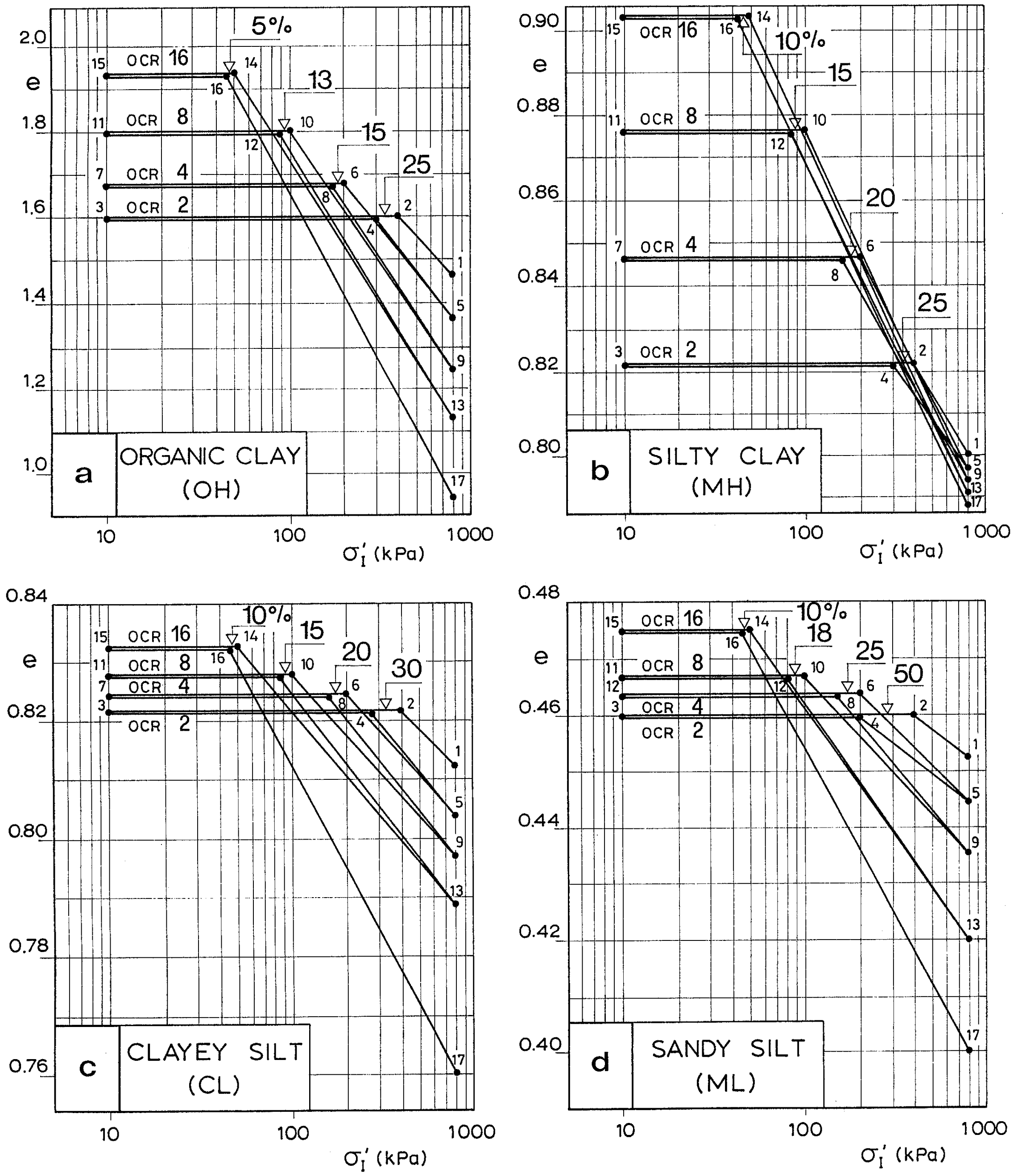

Fig. 12. Suction measurements in overconsolidated soils by means of modified triaxial cell

oedometer tests may be considered negligible in normally consolidated samples: as soon as undrained unloading is carried out, residual stress is greater than initial horizontal stress and lower than initial vertical stress, so that deformation mainly occurs along the vertical direction. In the case of overconsolidated specimens in anisotropic conditions, horizontal stress may be greater than vertical stress, so that some influence of soil-ring friction is possible on suction measurements with the oedometer.

Reduction of suction may derive from sustained creep: if effective isotropic residual stress acts for a long time, some contraction of the soil skeleton is possible, with consequent reduction of residual stress and some softening of the specimen.

The loss of suction generally increases as the plasticity index decreases, this effect may be explained in terms of pore fluid cavitation, since maintaining water tension in the pore space is more difficult when soil particles increase in size. Nevertheless, the distribution and size of voids close to the sample-air interface may have a great influence on the reduction of clay suction. A sketch of the soil-air-water interface during undrained unloading is given in Fig. 16: under residual stress U_R, the water menisci in connection with the air must all have the same curvature (Fig. 16a)). Equilibrium of forces along the axis of symmetry of any meniscus gives:

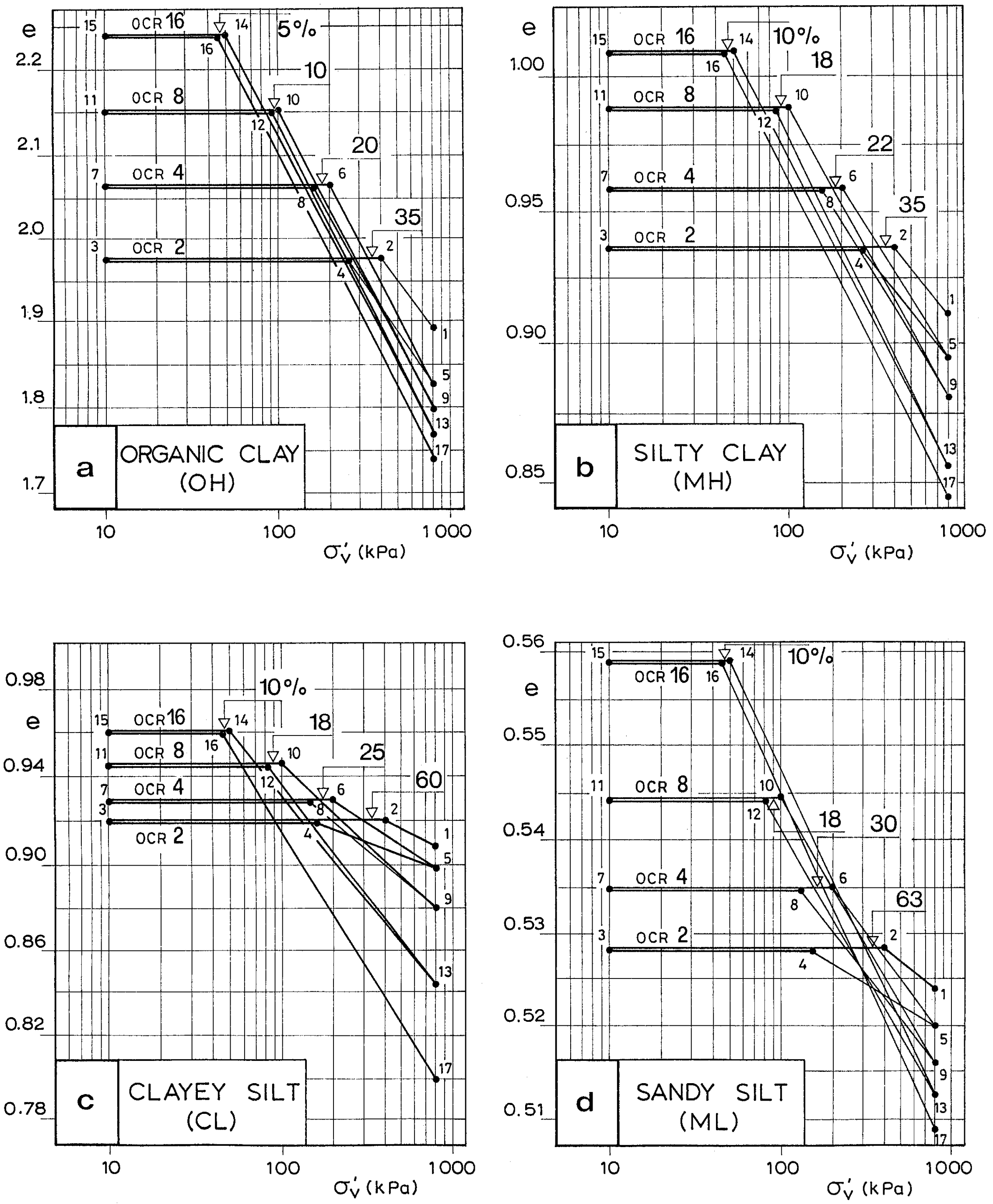

Fig. 13. Suction measurements in overconsolidated soils by means of modified oedometer

$$\pi d T \cos\alpha = U_R \frac{\pi d^2}{4} \qquad (21)$$

in which $d=2R\cos\alpha$. Therefore, the following equation is obtained:

$$R=\frac{2T}{U_R} \qquad (22)$$

with:

T=surface tension at the water-air interface;
α=angle of contact between soil and water;
d=diameter of the pore opening at the contact between soil and water;
R=radius of curvature of the meniscus.

From Eq. (22), R decreases as residual stress increases (Fig. 16b)), but the minimum value which may be achieved is $R=d_{\min}/2$ (Fig. 16c)), in which case $\alpha=0$ and the meniscus keeps minimum diameter $d_{\min}$ of the pore.

If the trend towards soil swelling requires a greater value of residual stress for equilibrium, the meniscus is not able to reduce its radius further and breaks; water withdraws inside the pore space and other menisci develop in the neighbouring smaller pore openings, to ensure equilibrium. The process involves a certain expan-

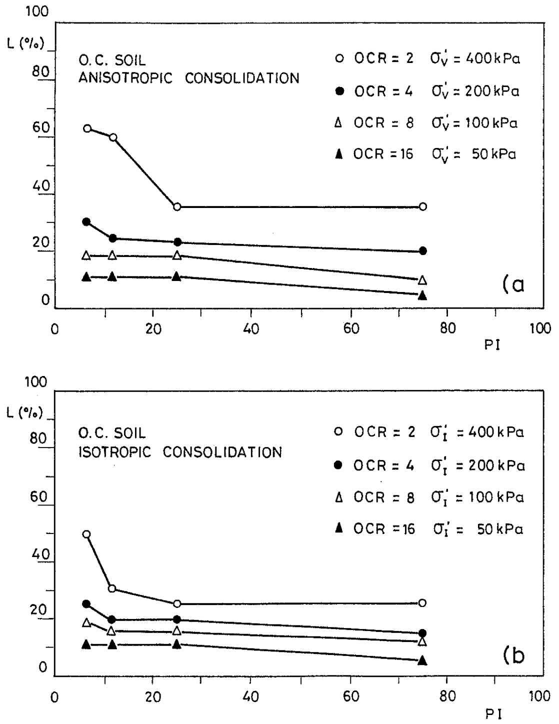

Fig. 14. Loss of suction in overconsolidated soils: a) modified oedometer, b) modified triaxial cell

sion of soil structure, with a general reduction in residual stress: if relative displacements occur between soil particles, as in the case of undrained unloading from normal compression in anisotropic stress conditions, the probability of breakage of water menisci increases in proportion to the consolidation stress level, thus providing greater reduction in suction.

INFLUENCE OF SOIL STRUCTURE

Undisturbed soils are naturally deposited during geologic processes: a "*fabric*" is attained depending on clay minerals and depositional environment. Fabric therefore refers only to the geometric arrangement of the soil particles. Soils remain in the ground for very long periods of time and may undergo physical and chemical changes. These changes are known as "*ageing*" and include phenomena like creep, cementing, weathering and vibrations, which are equivalent to changes in the overconsolidation ratio at constant effective stress (Atkinson, 1993). Natural soils which have an initial "*fabric*" and have undergone "*ageing*" are often called "*structured*," because they possess a "*structure*" which takes into account both particle arrangement and interparticle strength. Reconstituted samples, which have been completely remoulded and reconsolidated, do not possess "*structure*."

Ageing may influence residual stress because of the induced overconsolidation; from this point of view, ageing may attenuate disturbance, whereas fabric may increase it because of the presence of larger voids with respect to the remoulded soil condition.

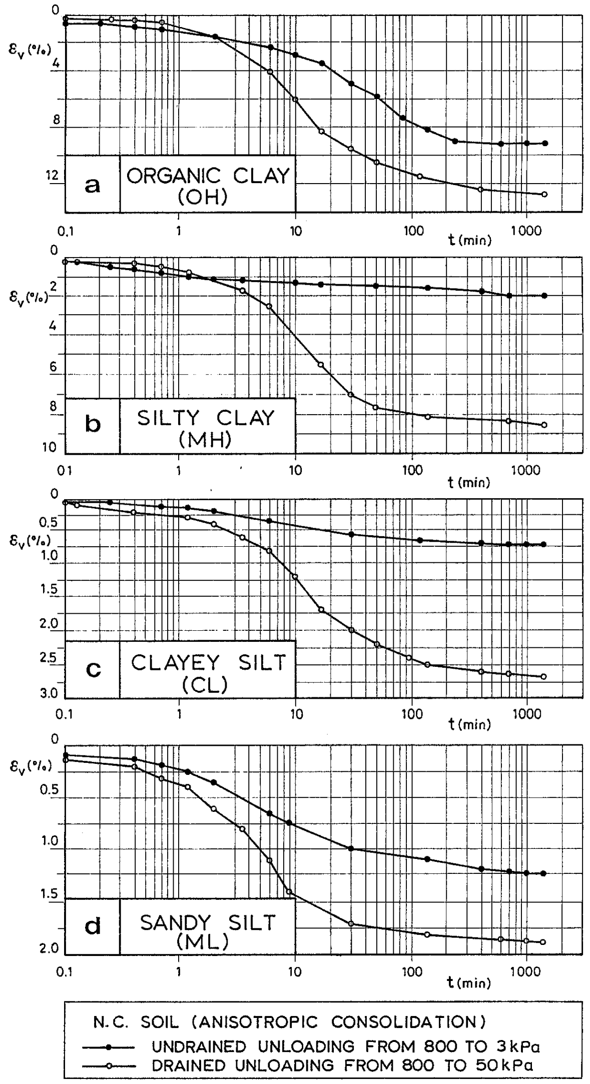

Fig. 15. Comparison between drained and undrained axial extension strain of normally consolidated soils subjected to same unloading in oedometer

To investigate the influence of structure on stress relief disturbance, some undisturbed clay samples coming from the Venetian plain were tested. These samples, with different plasticity and stress history (Table 2), were tested in normally consolidated conditions by performing undrained unloading from a stress level equal to the best estimation of in situ preconsolidation stress. In this manner, the ageing effect was almost erased and only the fabric became potentially significant. The obtained loss of suction for undisturbed samples is shown in Fig. 17, together with that of the remoulded samples previously discussed (Fig. 11).

The results related to anisotropic stress conditions (Fig. 17a)) indicate greater values of loss of suction in undisturbed soils than in remoulded ones. For the same plasticity index, comparison of preconsolidation stresses highlights the further loss of suction in undisturbed samples with respect to remoulded ones. Depending on plasticity index, the additional loss of residual stress varies in

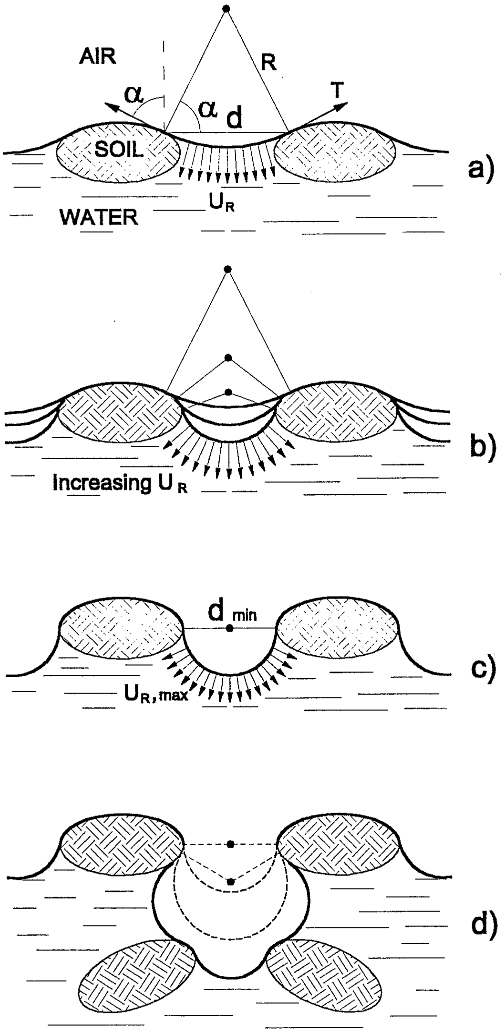

Fig. 16. Soil-water-air interface behaviour during undrained unloading: a) sample in equilibrium, all menisci having same curvature, b) withdrawal of menisci with increasing suction, c) maximum suction supported by a pore opening in relation to its minimum diameter, c) breakage of meniscus and achievement of equilibrium

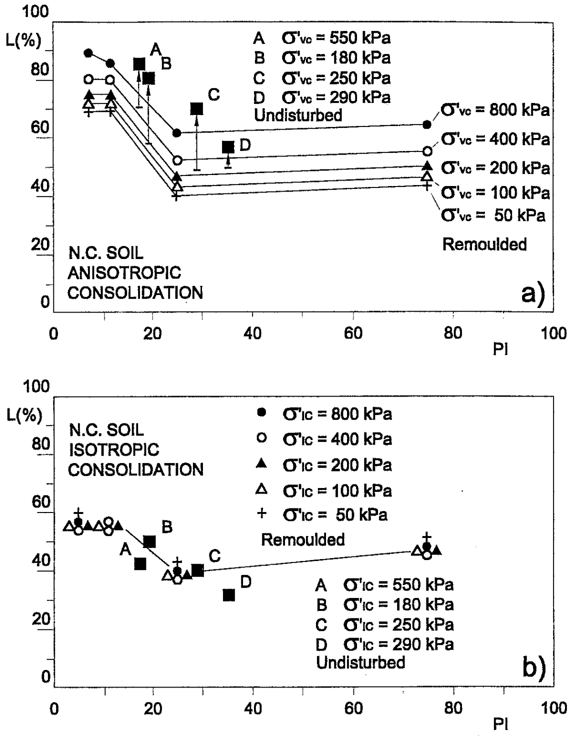

Fig. 17. Loss of suction in normally consolidated undisturbed clays and comparison with results obtained in remoulded soils: a) modified oedometer, b) modified triaxial cell

Table 2. Geotechnical properties of undisturbed natural soils

Soil	W_L (%)	W_P (%)	PI	C_C	C_S	σ'_v (kPa)	OCR	σ'_{vc} (kPa)
A	40	23	17	0.12	0.014	120	4.6	550
B	52	33	19	0.14	0.032	180	1.0	180
C	61	33	28	0.30	0.031	250	1.0	250
D	55	20	35	0.14	0.024	130	2.2	290

Note
W_L=Liquid limit
W_P=Plastic limit
PI=Plasticity index
C_C=Compression index
C_S=Swelling index
OCR=Overconsolidation ratio
σ'_v=In situ vertical effective stress
σ'_{vc}=In situ preconsolidation stress

the range $5\% < \Delta L < 20\%$. This effect, which is more significant in soils of low plasticity, may be explained by the larger voids which exist in natural clay fabrics with respect to remoulded ones, and by the shear strains which develop to change the stress conditions from anisotropic to isotropic.

The results related to isotropic stress conditions are reported in Fig. 17b); in this case, the effect of structure was less influential and the loss of suction values in undisturbed soil are in good agreement with those of remoulded ones. Also in this case, the stress level, reached before undrained unloading, seems to have less influence.

CONCLUSIONS

Undrained unloading of effective confining stress (*perfect sampling*) induces tensional disturbances which have repercussions on residual pore pressure in saturated cohesive soils. This particular aspect of sampling disturbance was investigated in this paper by means of laboratory experiments on reconstituted natural soils of varying plasticity. Suction was selected as a reference parameter for disturbance evaluation and an indirect measurement technique was employed in order to investigate the influence of various stress paths on final suction. Controlling the swelling of *perfect* samples connected to a water supply, a number of suction measurements were performed using a modified oedometer and a triaxial device. The influences of stress condition, stress level, stress history and plasticity on final suction were examined by introducing a comparison parameter (L) accounting for suction loss with respect to current confining stress.

Laboratory results indicate great sensitivity to stress disturbance in normally consolidated soils. For anisotropic consolidation, suction loss is mostly related to stress level and plasticity index, whereas for isotropic consolidation, it becomes independent of stress level. Normally consolidated soils with low plasticity in anisotropic stress conditions and high stress levels may show suction losses as high as 90%, to which corresponds a reduction in undrained strength of about 40% of the undisturbed value before undrained unloading. It is evident that, in such cases, laboratory recompression is required to reduce stress disturbance.

In overconsolidated soils, little loss of suction is expected at $OCR>4$, in which case the observed maximum L values, no higher than 20%, are independent of plasticity index and stress conditions. The reduction in undrained strength is negligible in this case, the final undrained strength being about 95% of the undisturbed value before undrained unloading.

For slightly overconsolidated soils, greater loss of suction was found, up to 50% or 60%, depending on stress level, stress conditions and plasticity index. For these soils, a reduction in undrained strength of about 20% of the undisturbed value before undrained unloading may be expected.

Structure in soil is characterised by the fabric which develops during deposition and by ageing, which takes into account modifications occurring over time. Ageing may influence residual stress because of induced overconsolidation; from this point of view, ageing may attenuate disturbance, whereas fabric may increase it, because of the presence of larger voids with respect to the remoulded soil condition. However, further research is needed in this field and anisotropic consolidations in a triaxial cell, rather than in the oedometer, may lead to improved suction appraisal.

REFERENCES

1) Atkinson, J. (1993): The Mechanics of Soils and Foundations, McGraw-Hill Book Company, London.
2) Atkinson, J. H., Allman, M. A. and Böese, R. J. (1992): "Influence of laboratory sample preparation procedures on the strength and stiffness of intact Bothkennar soil recovered using the Laval sampler," Géotechnique, Vol. 42, No. 2, pp. 349–354.
3) Baligh, M. M., Azzouz, A. S. and Chin, C. T. (1987): "Disturbances due to ideal tube sampling," J. of Geotech. Engrg., Vol. 113, No. 7, pp. 739–757.
4) Barden, L. and McGown, A. (1973): "Microstructural disturbance in soft clays resulting from site investigation sampling," Proc. of Int. Symp. on Soil Structure, Gothenburg, August 1-2, pp. 205–215.
5) Bjerrum, L. (1973): "Problems of soil mechanics and construction on soft clays and structurally unstable soils. General Report," Proc. of 8th Int. Conf. on SMFE, Moscow, 1973, Vol. 3, pp. 111–159.
6) Carrubba, P. (1989): "Analisi del disturbo da campionamento nei terreni coesivi saturi," Tesi di Dottorato di Ricerca in Ingegneria Geotecnica, II Ciclo, Università di Padova, Padova.
7) Chandler, R. J. and Gutierrez, C. I. (1986): "The filter-paper method of suction measurement," Géotechnique, Vol. 36, No. 2, pp. 265-268.
8) Chandler, R. J., Harwood, A. H. and Skinner, P. J. (1992): "Sample disturbance in London Clay," Géotechnique, Vol. 42, No. 4, pp. 577-585.
9) Chen, F. H. (1988): Foundations on Expansive Soils, Elsevier, Amsterdam.
10) Clayton, C. R. I., Hight, D. W. and Hopper, R. J. (1992): "Progressive destructuring of Bothkennar clay: implications for sampling and reconsolidation procedures," Géotechnique, Vol. 42, No. 2, pp. 219-239.
11) Croney, D. and Coleman, J. D. (1960): "Pore pressure and suction in soil," Proc. of Conf. on Pore Pressure and Suction in Soils. Institution of Civil Engineers, London, March 30-31, 1960, pp. 31–37.
12) Fredlund, D. G. and Rahardjo, H. (1993): Soil Mechanics for Unsaturated Soils, John Wiley & Sons, New York.
13) Fredlund, D. G. and Wong, D. K. H. (1989): "Calibration of thermal conductivity sensors for measuring soil suction," Geotech. Testing J., Vol. 12, No. 3, pp. 188–194.
14) Graham, J. and Lau, S. L. K. (1988): "Influence of stress-release disturbance, storage, and reconsolidation procedures on the shear behaviour of reconstituted underwater clay," Géotechnique, Vol. 38, No. 2, pp. 279–300.
15) Hight, D. W., Böese, R., Butcher, A. P., Clayton, C. R. I. and Smith, P. R. (1992): "Disturbance of the Bothkennar clay prior to laboratory testing," Géotechnique, Vol. 42, No. 2, pp. 199–217.
16) Holtz, R. D., Jamiolkowski, M. B. and Lancellotta, R. (1986): "Lessons from oedometer tests on high quality samples," J. of Geotech. Engrg., Vol. 112, No. 8, pp. 768–776.
17) Kirkpatrick, W. M. and Khan, A. J. (1984): "The reaction of clays to sampling stress relief," Géotechnique, Vol. 34, No. 1, pp. 29–42.
18) Ladd, C. C. and Foot, R. (1974): "New design procedure for stability of soft clays," J. of Geotech. Engrg. Div., Vol. 100, No. GT7, pp. 763–786.
19) Ladd, C. C., Foot, R., Ishihara, K., Schlosser, F. and Poulos, H. G. (1977): "Stress-deformation and strength characteristics," Proc. of 9th Int. Conf. on SMFE, Tokyo, Vol. 2, pp. 421–494.
20) Ladd, C. C. and Lambe, T. W. (1963): "The strength of undisturbed clay determined from undrained tests," Symp. on Laboratory Shear Testing of Soils, ASTM, Ottawa, September 9, 1963, pp. 342–371.
21) Lambe, T. W. (1961): "Residual pore pressures in compacted clay," Proc. of 5th Int. Conf. on SMFE, Paris, July 17–22, Vol. 1, pp. 207–211.
22) La Rochelle, P., Leroueil, S. and Tavenas, F. (1986): "A technique for long-term storage of clay samples," Can. Geotech. J., Vol. 23, No. 4, pp. 602–605.
23) Nakase, A., Kusakabe, O. and Nomura, H. (1985): "A method for correcting undrained shear strength for sample disturbance," Soils and Foundations, Vol. 25, No. 1, pp. 52–64.
24) Ricceri, G. and Butterfield, R. (1974): "An analysis of compressibility data from a deep borehole in Venice," Géotechnique, Vol. 24, No. 2, pp. 175–191.
25) Skempton, A. W. (1961): "Horizontal stresses in an overconsolidated Eocene clay," Proc. of 5th Int. Conf. on SMFE, Paris, July 17–22, Vol. 1, pp. 351–357.
26) Skempton, A. W. and Sowa, V. A. (1963): "The behaviour of saturated clays during sampling and testing," Géotechnique, Vol. 13, No. 4, pp. 269–290.
27) Wood, D. M. (1990): Soil Behaviour and Critical State Soil Mechanics, Cambridge Univ. Press, Cambridge.