USE OF ISOTROPIC STRESS STATE FRAMEWORK TO EVALUATE THE EFFECT OF SUCTION ON SOME MECHANICAL PARAMETERS OF SAINTE-ROSALIE CLAY SUBMITTED TO CONFINED COMPRESSION

by

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ABSTRACT

This paper reports experimental data gathered while performing isotropic tests on a heavy agricultural clay soil from Quebec province (Eastern Canada). Tests performed were one-dimensional compression, isotropic compression, and K_0. Tests on saturated soil samples were performed using conventional procedures; tests on unsaturated samples were performed after the desired suction was applied to the samples. Samples used in all the tests were processed at the same suction before the selected suction was applied. For the one-dimensional compression tests, the chosen suction was applied by moistening or drying while the axis translation method was used for applying suction to soil samples in isotropic compression and K_0 tests.
Results show that soil plastic and elastic parameters are suction dependant. In addition, strength of Sainte-Rosalie clay measured under different suctions in K_0 tests quantified the significant strength gain observed in the field when this material evolves from wet to dry conditions.

Keywords: compression, critical state theory, isotropic stress state, stress, strain.

INTRODUCTION

Excessive soil compaction in the crop zone adversely affects crop production : this fact has been well documented by many researchers throughout the world. Efforts to reduce these detrimental effects have led some researchers to focus their work on the mechanical behavior of agricultural soils through field and laboratory tests.
Research activity carried out on the mechanical behavior of agricultural soils has allowed a broad understanding of principles and factors affecting agricultural soil behavior. The knowledge gathered in studying the compressibility of agricultural soils has consequently paved the way for application of the critical state theory to the analysis of agricultural soil behavior (Kurtay and Reece, 1970; Reece, 1977; Hettiarachi and O'Callaghan, 1980; Hettiarachi, 1987). Critical state theory is described elsewhere (Wulfsohn, 1994). Application of this theory in analyzing agricultural soil behavior was based on the total stress approach (Kirby, 1989; 1991).

All agricultural soil scientists, however, did not agree to this approach. Some claimed that agricultural soils were essentially unsaturated and that critical state theory, primarily developed for describing the mechanical behavior of saturated soil was therefore inappropriate for describing the mechanical behavior of agricultural soils (Towner, 1983; McKyes, 1986; Kirby, 1989). This point of view was backed up by the work developed by civil engineering for describing the mechanical behavior of unsaturated soils (Alonso et al., 1990 ; Toll, 1990 ; Wheeler and Sivakumar, 1995). In effect, the work done in geotechnical engineering has shown that the effective stress (σ - u_w) stated by Terzaghi (1925) for a saturated soil can be reinterpreted as a stress state variable for the same soil rather than a physical law (Fredlund and Rahardjo, 1993). Based on this new vision in conceptualizing the soil mechanical behavior, unsaturated soil mechanical behavior can consequently be described using three identifiable stress variables because unsaturated soil is made up of air, water, and solid grains; the three stress variables are the following :

$(\sigma - u_a)$ and $(u_a - u_w)$ (1)

$(\sigma - u_w)$ and $(u_a - u_w)$ (2)

$(\sigma - u_a)$ and $(\sigma - u_w)$ (3)

where

σ is the total stress

u_a is the pore air pressure

u_w is the pore water pressure

The first pair of terms in equation (1) is the most used in practical engineering since it separates the effect due to changes in normal stress from the effect due to change in pore water pressure (Wulfsohn et al., 1996). This new approach in dealing with unsaturated soil mechanical behavior has been used in this paper while studying the mechanical behavior of Sainte-Rosalie clay within the isotropic stress state framework.

OBJECTIVE

The objective of the investigation was to determine the effect of suction on the mechanical behavior of deep layers of agricultural soil. The isotropic stress state framework was used according to the new approach developed by geotechnical engineering in analyzing the mechanical behavior of unsaturated soil (Alonso et al., 1990 ; Wheeler and Sivakumar, 1995). Because the investigation focused on the mechanical behavior of an agricultural soil for isotropic stress state, soil samples were processed with the objective of representing the agricultural field condition below the plow pan of an experimental field where soil compaction was monitored.

MATERIALS AND METHODS

Static compaction of soil samples

The studied soil was Sainte-Rosalie clay. It is a gley solic soil from Saint Simon, a small village located 60 km (40 miles) from East Montreal, Quebec province, Canada. The soil has not shown any significant swelling properties on wetting. Its grain size analysis is shown in figure 1 and its geotechnical properties are displayed in table 1.

The soil has first been dried in a soil bin for more than 6 months in the Department of Soils and Agri-Food Engineering, Laval University, Quebec city, Canada. Two categories of samples have been processed :

- one category was made of 3.81 cm (1.6 in) diameter and 7.1 cm (2.8 in) high samples; this sample category was intended to be used in K_0 and isotropic compression tests. K_0 also known as the coefficient of lateral stress at rest is the ratio of soil horizontal stress over soil vertical stress; it is defined for the soil at rest.

- the other category was made of 3.5 cm (1.5 in) diameter and 2.54 cm (1 in) high samples; this sample category was intended to be used in one-dimensional compression tests.

Samples of both categories were processed using a static compaction device. They were compacted up to 1.5 g/cm^3 dry density. This dry density represented that of 25 to 40 cm depth of the experimental field where soil compaction was monitored; it resulted from soil compaction induced by farm equipment trafficking. Gravimetric water content during compaction was 21%. This water content represented the common water content of soil during agricultural activities. Degree of saturation was 0,67 and suction of soil samples was 300 kPa according to the soil suction curve (Figure 2). Soil suction was determined using the paper-filter method (Fredlund and Rahardjo, 1993; Marinho, 1994; Chandler and Guttierez, 1996). A water content - dry density relationship was also performed. It was drawn from a standard Proctor test (Figure 3).

Samples for isotropic compression and K_0 tests were compacted in four layers to ensure the best standard homogeneity. Each layer was compacted using a 240 kPa pressure. The device used for static compaction did not allow each layer to settle beyond a pre-set level upon compaction. This allowed samples to be compacted only up to the desired dry density. The top of each layer was carefully scarified after placement. The best homogeneity along the interface joining two adjacent layers was obtained due to this process. After compaction, the mold was dismantled and the sample was collected.

As far as samples for one-dimensional compression are concerned, an oedometer ring was mounted at the end of the mold, which allowed soil samples to be directly compacted in the oedometer rings. Samples were compacted in a single layer. They were compacted using 240 kPa of pressure. Settlement of each sample was pre-set, which allowed soil to be compacted up to the desired dry density. After compaction, the mold was removed and the sample with the oedometer ring collected together.

One - dimensional compression tests

Compression tests were performed using Rear Loading Consolidation Frame. They were tested under two soil conditions : saturated or unsaturated.

One - dimensional compression on saturated soil

To perform the test on a saturated soil specimen, it was placed in the cell where it was submerged with water. The soil specimen stayed in that condition for 24 hours until the test was started. This length of time was chosen to allow saturation of the specimen without destroying its structure.

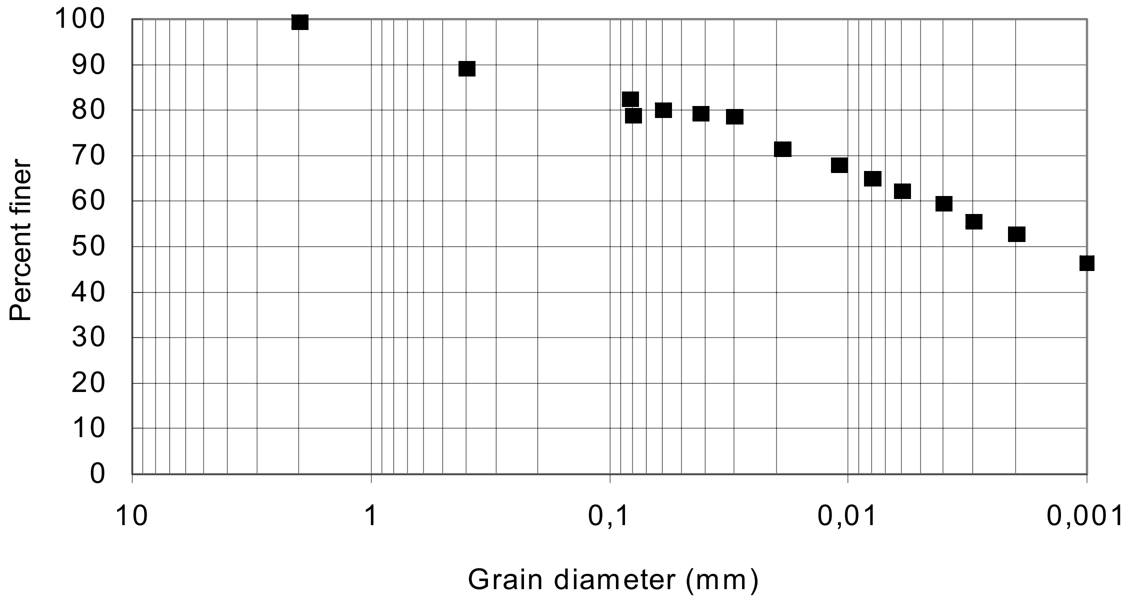

Figure 1. Grain size analysis of Sainte-Rosalie clay

One - dimensional compression on unsaturated soil

To perform the test on an unsaturated soil specimen at a suction of 300 kPa, the specimen was placed in the cell immediately after processing since the specimens were processed at 21% water content (suction ≈300 kPa). To test the specimen at a lower suction, the specimen was first moistened and placed in a chamber for 30 to 120 minutes. The ambient temperature of the chamber was 7-9 ^{o}C and its relative humidity was 50%. The stay in the chamber allowed the specimen moistening to be homogenized before testing. For testing the specimen at a suction higher than 300 kPa, the specimen was allowed to dry for 30 to 120 minutes in a room at 21-23 ^{o}C ambient temperature and 70% relative humidity. In either case, the specimen was then placed in the cell after this first phase.

The inner side of the cell wall was cushioned with wetted cotton to maintain the appropriate humidity around the sample throughout the test. Care was taken that this wetted cotton did not touch the ceramic porous stone on which the soil specimen rested. The cell was then wrapped with a translucent plastic foil and stuck to the outer side of cell wall with a rubber band. This process helped maintain a constant atmospheric condition around the specimen during the test, which lasted 2 to 3 weeks. In either test condition, loads were incrementally applied to the specimen, which varied in load increment ratio from ½ to 1. At each loading step, the load application lasted 24 hours. Therefore, a certain amount of secondary compression was found during assessment of soil compression.

Table 1. Physical data of Sainte-Rosalie clay

Parameters	Value
Sand fraction	20%
Silt fraction	27%
Clay fraction	53%
Internal friction angle ϕ’	28^o
Cohesion (kPa)	0
Activity	0.4
Liquid limit	45%
Plastic limit	24%
Plasticity Index	21%
Void Ratio	0.84
Porosity	0.44
Organic matter content	3.2%
Average pore diameter (mm)	0.037

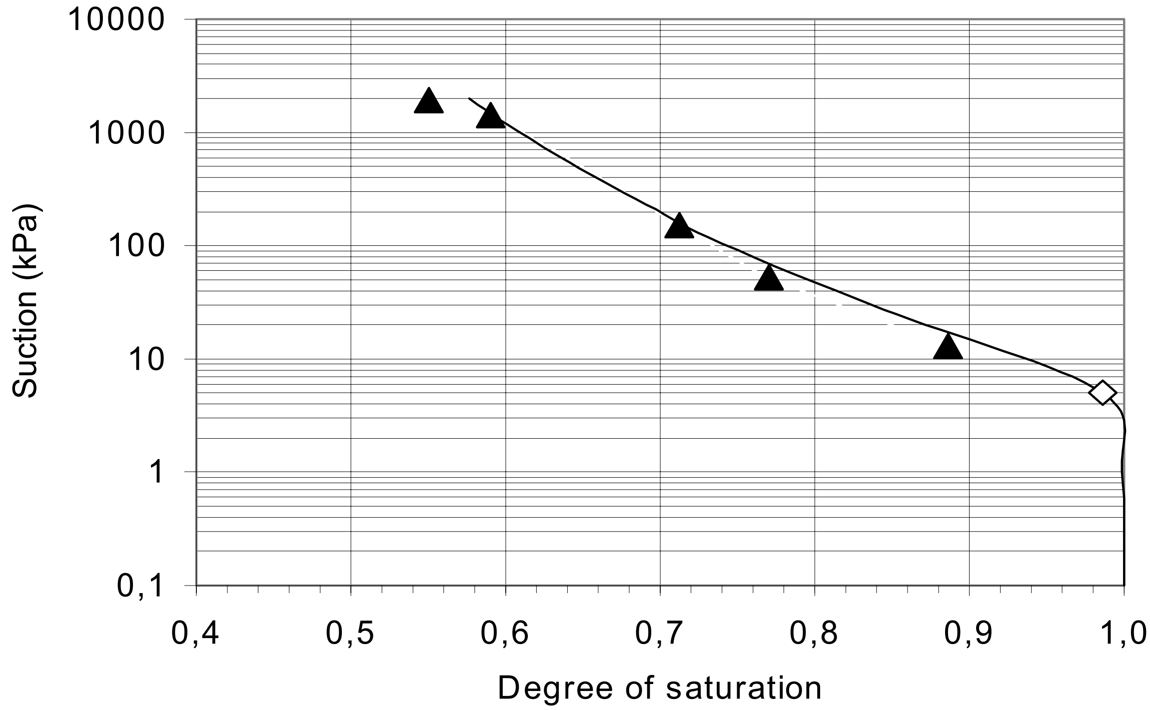

Figure 2. Soil-characteristic curve of Sainte-Rosalie clay

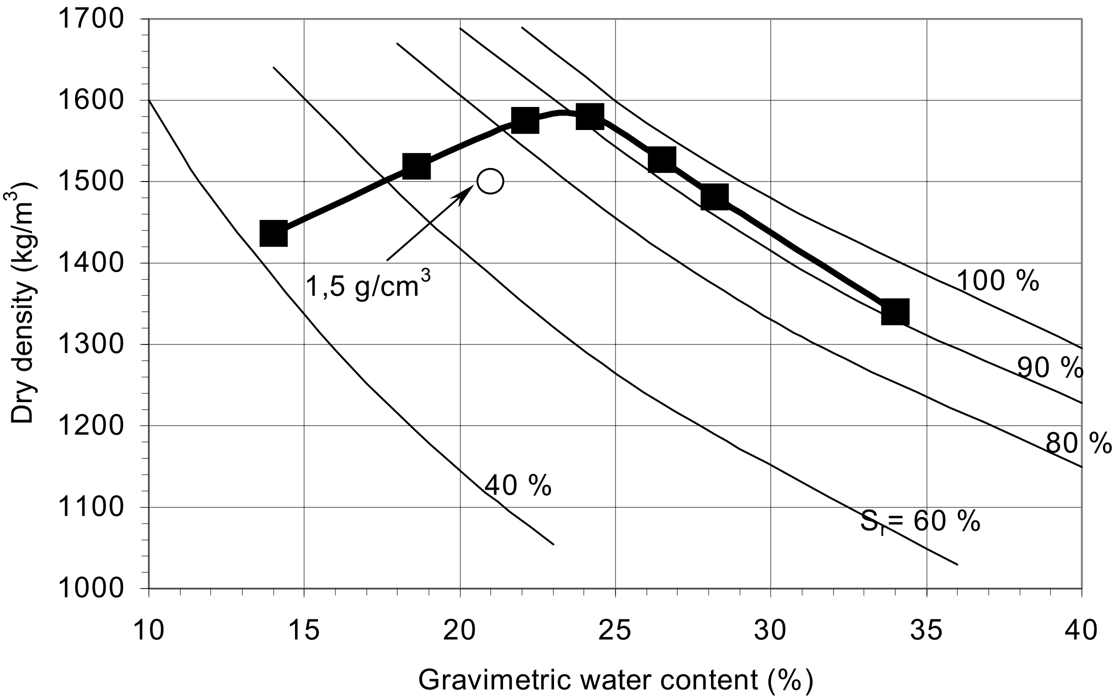

Figure 3. Proctor compaction curve of Sainte-Rosalie clay
Key : S_r = degree of saturation

Isotropic compression tests

Isotropic compression on saturated soil samples

These tests were done using the conventional triaxial cell. The procedure for running tests on the saturated soil was as follows: the sample was placed in a conventional triaxial test. A 10 kPa hydrostatic pressure and a 2 kPa back-pressure were both applied to the sample. This allowed an 8 kPa gradient, which triggered water to circulate from bottom to top in the sample. Drainage on top of the sample was open at the beginning of water circulation. It allowed air in the sample to be driven out due to the incoming water. Drainage was terminated when water started to escape. Then the hydrostatic pressure and back-pressure were both increased in steps of 25 kPa. Both pressures at each step were maintained for 3 to 4 hours. More water was then allowed into the sample. Before increasing both pressures to the next step, the sample level of saturation was first checked by computing the B Skempton parameter (Head, 1986). It was found that the B Skempton parameter reached 0.95 to 0.97 when hydrostatic pressure and back-pressure respectively reached 210 kPa and 202 kPa. The soil sample was, therefore, technically saturated. From this point, increasing hydrostatic pressure was progressively applied to the sample. The increment ratio of increasing confining pressure varied from ½ to 1. The maximum increment of confining pressure was not larger than 50 kPa. The sample stayed at each step for 24 hours. Care was taken to determine the void ratio at each loading step for plotting the e-ln p curve of the test: e is the void ratio while p is the mean stress. During isotropic compression, the sample bottom drainage remained open. The test lasted approximately two weeks.

Isotropic compression on unsaturated soil samples

A double wall-triaxial cell was used to carry out triaxial tests for the unsaturated soil samples. It allowed application of the "axis translation method proposed by Hilf (1956)". After the soil sample was mounted in the triaxial cell, pore water pressure u_w equal to the atmosphere pressure was applied at the base and the top of the specimen through porous ceramics with an entry value of 500 kPa. The air pressure u_a was applied to the sample through a hole in the rubber membrane and a diffuser made of geotextile at the mid-height of the specimen. Such a set-up was chosen to decrease the drainage length and consequently the time necessary to achieve equilibrium during the different phases of the tests. The air pressure selected was equal to the desired matrix suction $s = u_a - u_w$. The cell pressure, σ_3 , taken was equal to the sum of air pressure and the desired net confining pressure $(\sigma_3 + u_a)$. The vertical stress was applied by a triaxial compression frame.

Suction during isotropic compression was applied as follows. At the beginning of the procedure, a net confining stress of 5 kPa was applied in the triaxial cell. The degree of saturation at that time was 67 %. The air pressure was applied in steps of 10 kPa with duration at each step being 15 minutes. To keep the piston applying axial load in contact with the sample, a 5 kPa axial stress in excess of the cell pressure was maintained during application of air pressure. When the air pressure corresponding to the desired suction was reached, the soil specimen was maintained under this condition until sample water content and air pressure came to equilibrium. In fact, during air pressure application, water was driven out of the sample. As long as drainage continued, it was the sign that the desired suction was not fully applied yet. It was considered that the desired suction was applied to the sample only when air pressure and sample water content reached equilibrium. The drainage usually took approximately 2 weeks for stabilization to occur (figure 4).

Isotropic compression was performed as follows. After stabilization, increments of lateral pressure (σ_3) were applied to the sample. The increment ratio varied from ½ to1; each loading step was applied in increments of 10 kPa, with the maximum applied increment being 50 kPa per day. Once a 50 kPa step was reached, the pressure was maintained for 2 days to ensure that both water exchanges and volume changes. During increases of lateral pressure, the vertical pressure (σ_1) was also increased in such a way that the 5 kPa axial stress in excess of the cell pressure was always maintained. The volume change of the sample was measured externally with a deflectometer.

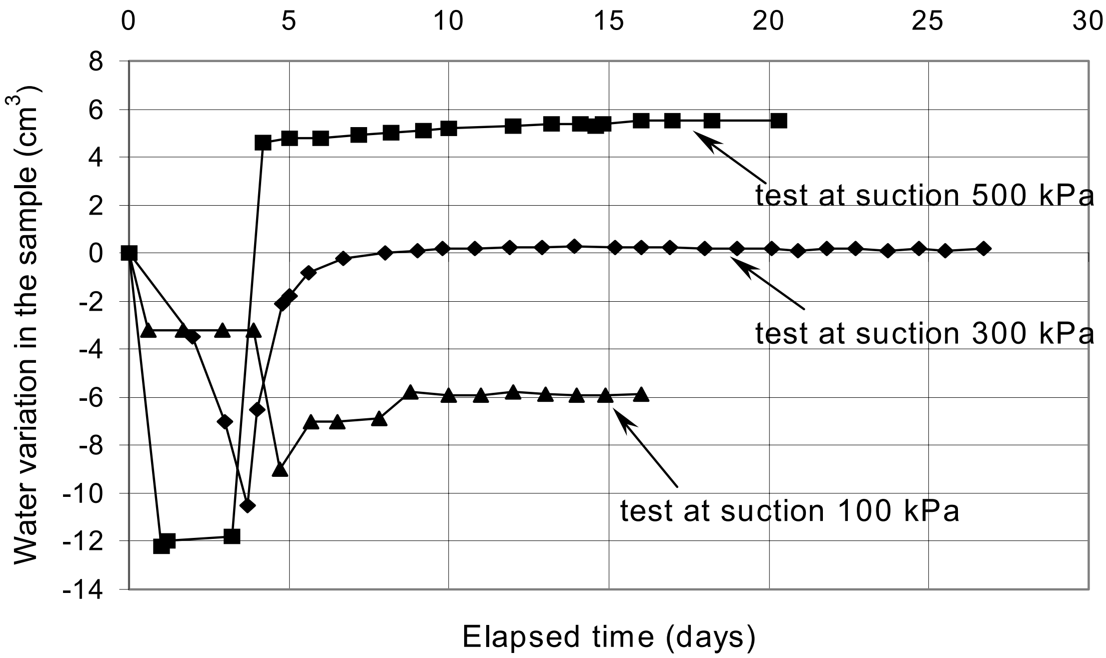

Figure 4. Variation of sample water contents during suction application in isotropic compression tests

Key : + corresponds to water drainage

- corresponds to water absorption

The volume change of the pore water was measured with burettes connected to the cell base and the top cap of the sample. In order to flush out any diffused air bubbles that formed under the porous stones, spiral grooves were connected on the base of the burette in a closed circuit of tubes with a peristaltic pump, thus allowing a gentle circulation of water under the stones and the flushing out of air bubbles. Each entire test lasted 4 to 5 weeks.

K_0 tests

Equipment

Equipment needed for testing samples under K_0 condition was a standard triaxial cell. Two small metallic flexible supports were attached to the sample for monitoring its diameter change during the test. These two small metallic flexible supports enclosed the sample in the cell during the test at mid-height. Axial pressure on the sample was applied by a piston connected to a mechanical press while radial pressure was applied by a vertical motion of mercury flasks.

Sample saturation

Saturation of the sample was performed the same way as in isotropic compression of saturated sample.

Application of suction to a sample

The application of suction was carried out according to the procedure described in the previous section on isotropic compression of unsaturated soil. The difference was in the fact the suction was not applied through the mid-height geotextile but through the top and bottom porous ceramics.

Sample compression

Application of radial pressure was triggered by the metallic flexible supports once a 0.1 µm diameter change occurred. This diameter change triggered the vertical motion of mercury flasks which applied radial pressure to bring the sample diameter back to its initial dimension. A deflectometer attached to a piston allowed sample height to be monitored. A 0.1 µm change of sample height triggered the application of axial pressure to bring the sample height back to its initial dimension. During testing, the equipment monitoring changes of sample height and diameter were actually connected to a LVDT (Linear Variation Differential Transformer). Electrical signals from this equipment were regularly sent to the LVDT during testing; once a dimension change reached 0.1 µm, this was recorded by a relay; depending on which parameter the change occurred, the relay in turn triggered the motion of either axial press or flasks which brought the sample back to its initial dimension.

In the case of a saturated soil sample, compression was undertaken immediately following sample saturation. During testing, drainage of interstitial water was allowed through top and bottom of the sample. Both sample top and bottom were connected to outside burettes. The volume of water flushed out of the sample was determined by the change of water level in the burettes. In the case of an unsaturated soil specimen, there was no change of water content since the water content in the sample was very low. The entire test lasted approximately 3 weeks.

RESULTS AND DISCUSSIONS

One-dimensional compression tests

The four tests data performed on samples are reported in table 2 and the curves are plotted in Figure 5. Yield stresses were determined using the Casagrande method. Data showed that yield stresses increased with decreasing water content; in other words, the yield stresses increased with increasing suction.

In an unsaturated state, the yield stress increased by 130 kPa when the water content of the Sainte-Rosalie clay decreased by 4% (table 2).

Table 2. Values of Sainte-Rosalie parameters under one-dimensional compression tests

Water content	σ'_c (kPa)	C_c	C_r
saturated	72	0.31	0.026
25%	180	0.32	0.025
21%	310	0.59	0.022
17%	440	0.26	0.035

Key: σ'_c = vertical yield stress
C_c = compression index
C_r = rebound index

The compression index (C_c) dramatically varied with change of water content. It was noticed that below the optimum water content (w = 23%), C_c increased with increasing water content while beyond optimum water content, C_c decreased with decreasing water content.

The rebound index (C_r) did not vary with changing water content. It was observed that below the optimum water content, C_r decreased with increasing water content while beyond the optimum water content, C_r increased with increasing water content.

The change of the plastic parameter (C_c) with suction observed during tests reported here was different from results from other experimental programs (Alonso et al., 1990; Cui and Delage, 1996; Wheeler and Sivakumar, 1995). It appears in this experimental program that as suction increased from zero, the plastic parameter increased up to a maximum at optimum water content, then decreased.

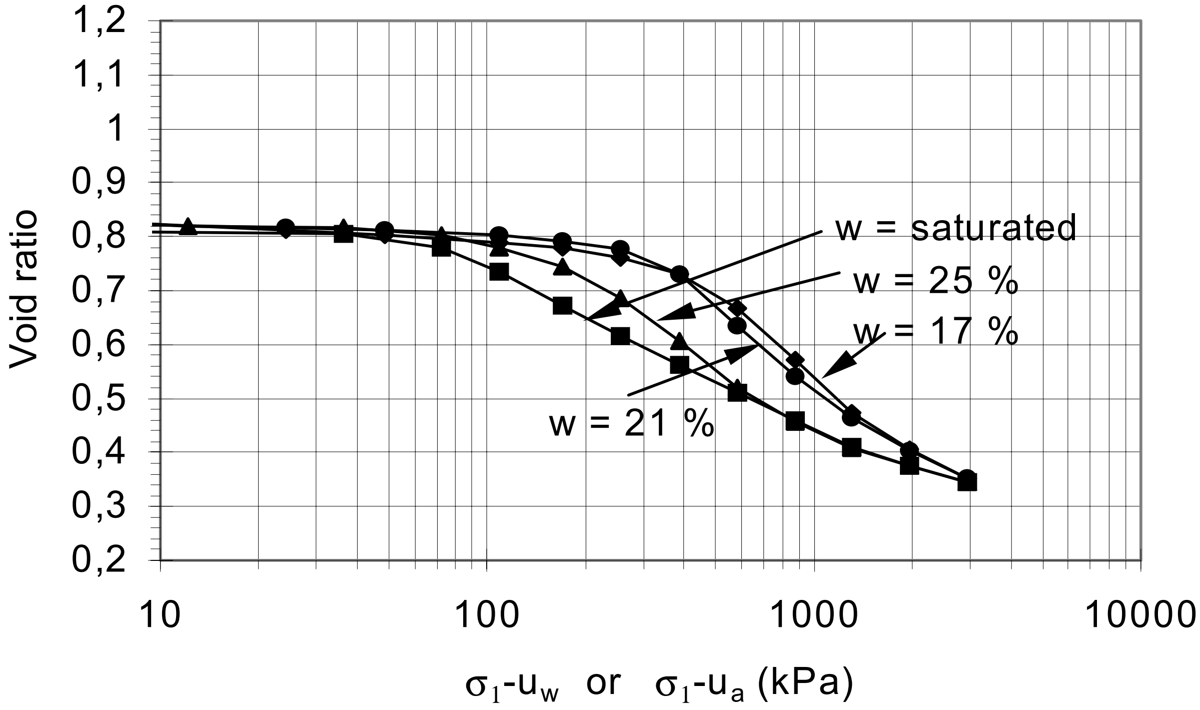

Figure 5. One-dimensional compression tests of Sainte-Rosalie clay
Key: σ_1 = vertical stress
u_w = pore water pressure
u_a = pore air pressure
w = gravimetric water content compression of Sainte-Rosalie clay performed at various suctions.

The increasing trend of C_c between zero suction (suction of saturated sample) and 300 kPa suction (approximate suction at the optimum water content) may be explained by the following fact: as water frees up the pore space, the soil became more susceptible to applied vertical stress. In addition, the high water content of the matrix in this range favors low friction among soil particles. These two effects were coupled to induce a compressibility which increased with reduced water content in this range of soil moisture content. Once the water content was less than optimum water content, the effect of matrix suction became the controlling factor of soil behavior; the soil behaved according to observations made by Alonso et al. (1990), Wheeler and Sivakumar (1995), and Cui and Delage (1996) on unsaturated soil behavior. Below the optimum water content, the matrix suction induced a negative pore pressure which exerted a tensile force at all air-water interfaces in the soil profile. The surface tension pulled the particles together providing an additional friction among the particles.

All the curves joined up at 2000 kPa vertical stress (Figure 5). The specific volume at that range of vertical stress is the final void ratio of Sainte-Rosalie clay upon compression since all curves join up at this stage whatever the stress path.

Isotropic compression tests

Tests results of the 3 tests performed on soil samples are displayed in table 3 with the resulting curves plotted in figures 6 - 8. It appears that the yield stress increased with increasing suction. Thus, as far as soil strength was concerned, the increase of suction corresponded to an increase of soil strength (figures 6, 7, and 8).

Table 3. Values of Sainte-Rosalie clay parameters under isotropic compression tests

Suction	λ (s)	σ'_{iso} (s)	κ (s)
0	0.13	70	0.012
300	0.24	170	0.010
500	0.22	190	0.012

Key: λ *(s)* = plastic parameter = slope of the normal consolidation line in the $p : \upsilon$ space (critical state theory)

σ'_{iso} = yield stress

κ *(s)* = elastic parameter = slope of the unloading-reloading line in the $p : \upsilon$ space (critical state theory)

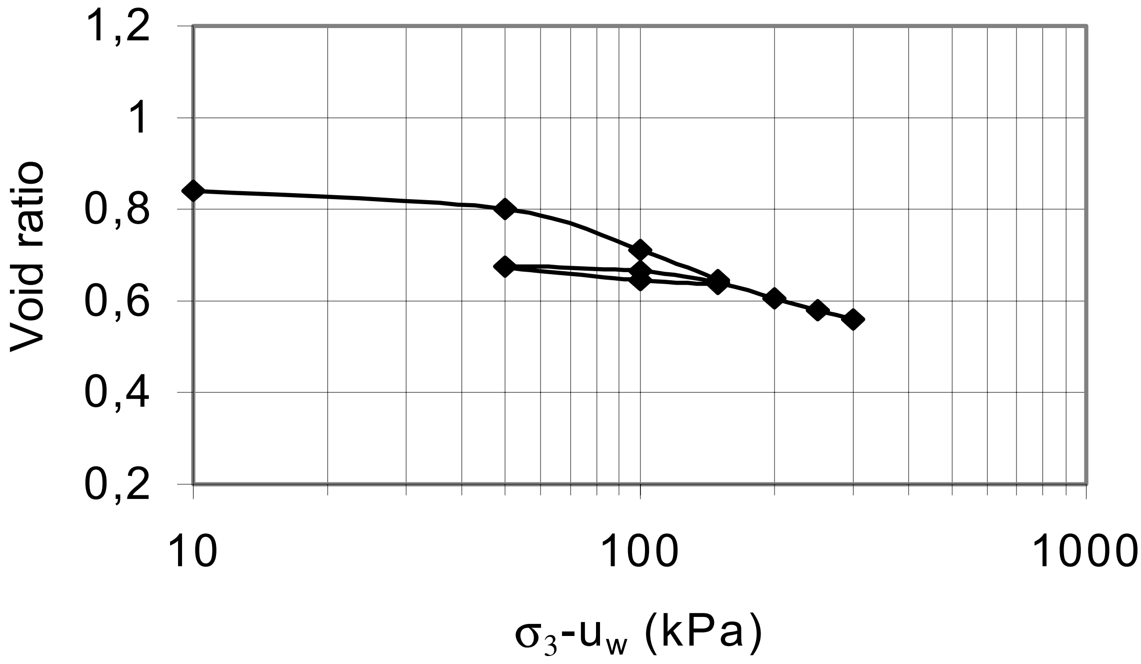

Figure 6. Isotropic compression of saturated Sainte - Rosalie clay
Key: σ_3 = confining pressure
u_w = pore water pressure

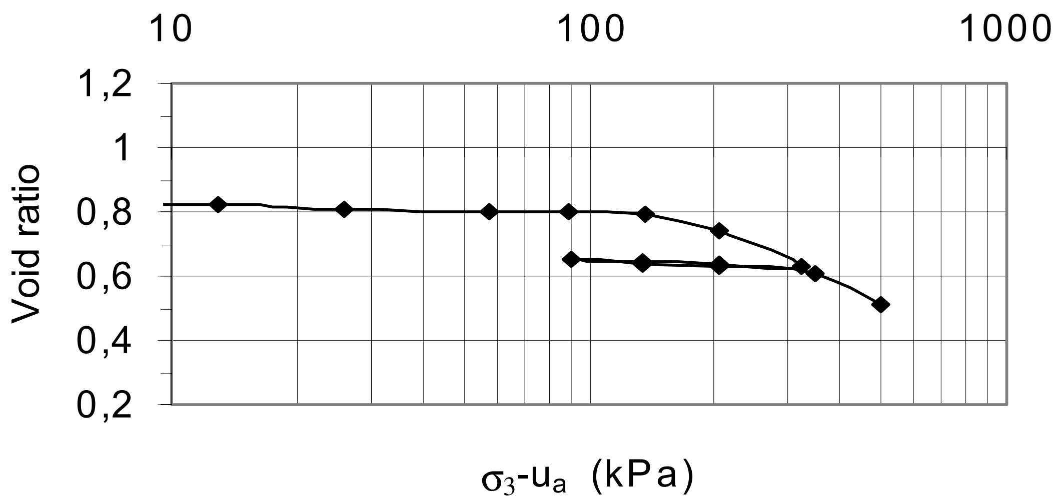

Figure 7. Isotropic compression of Sainte-Rosalie clay at suction 300 kPa
Key: σ_3 = confining pressure
u_a = pore air pressure

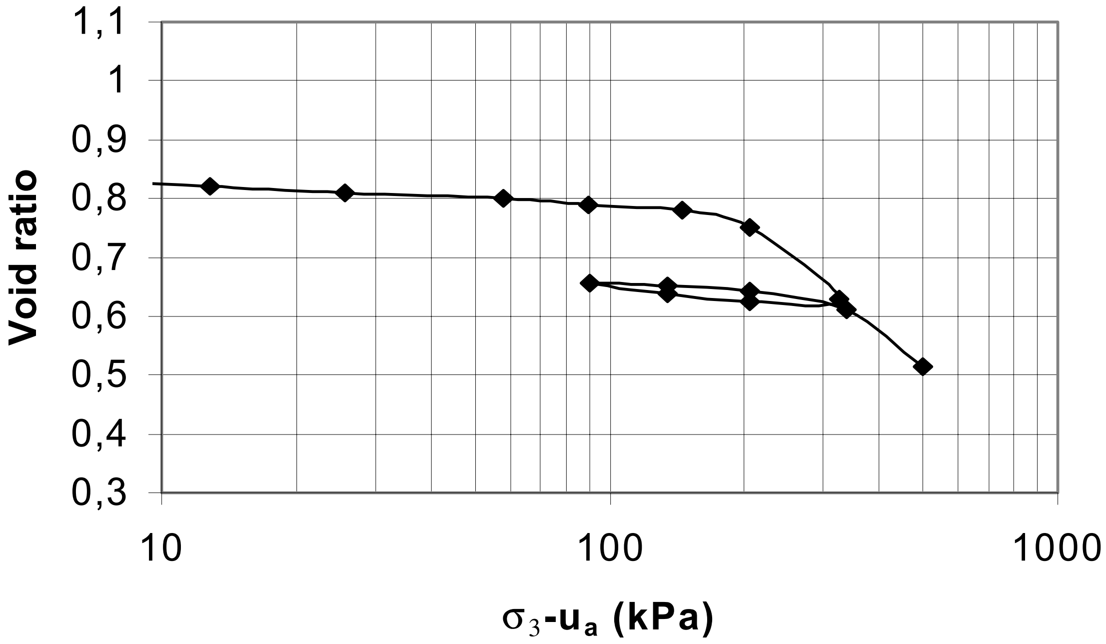

Figure 8. Isotropic compression of Sainte-Rosalie clay at suction 500 kPa
Key: σ_3 = confining pressure
u_a = pore air pressure

Although data are limited, it was observed that both the plastic parameter (λ) and the elastic parameter (κ) varied with suction (figures 9 and 10). In critical state theory, λ is the slope of normal consolidation line in the $p : \upsilon$ space, κ is the slope of unloading-reloading line in the $p : \upsilon$ space, p is the pressure and υ is the specific volume (1 + e). As mentioned above, the plastic parameter increased up to a suction corresponding to the optimum water content then decreased (figure 9) while the elastic parameter decreased down to suction corresponding to optimum water content then increased (figure 10). At he approximate suction which corresponded to the optimum water content (w = 23%), the evolution of either parameter (λ or κ) was reversed (figures 9 and 10). Over suctions, the variation of the plastic parameter (λ) was greater than the variation of elastic parameter (κ). In other words, variation of suction induced a greater variation on soil plasticity than it did on soil elasticity (figures 6 and 7). The plastic parameters derived from the K_0 test for saturated and unsaturated soil (respectively 0.14 and 0.15) correlated well with the general trend of λ.

K_0 tests

The K_0 test conducted on saturated samples yielded a yield stress of 70 kPa (figure 11). This value confirmed the yield stress obtained during isotropic compression on saturated sample (figure 6). The plastic parameter (λ) derived from K_0 test on the saturated soil sample was 0.14 while that of isotropic compression on the saturated sample was 0.13. The nearly same value of plastic parameter value obtained under these two different tests confirmed the general trend of the plastic parameter displayed at figure 9.

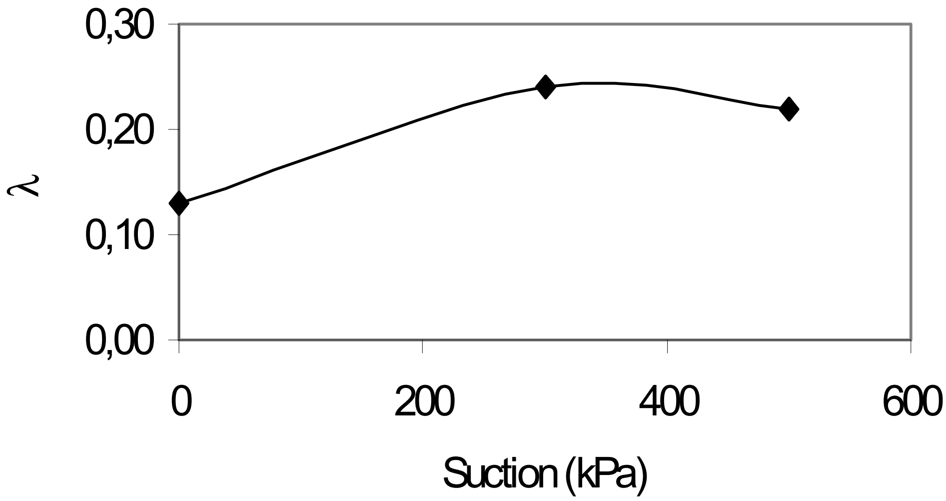

Figure 9. Variation of the plastic parameter with suction
Key : λ = slope of the normal consolidation line in the $p : \upsilon$ space of critical state theory

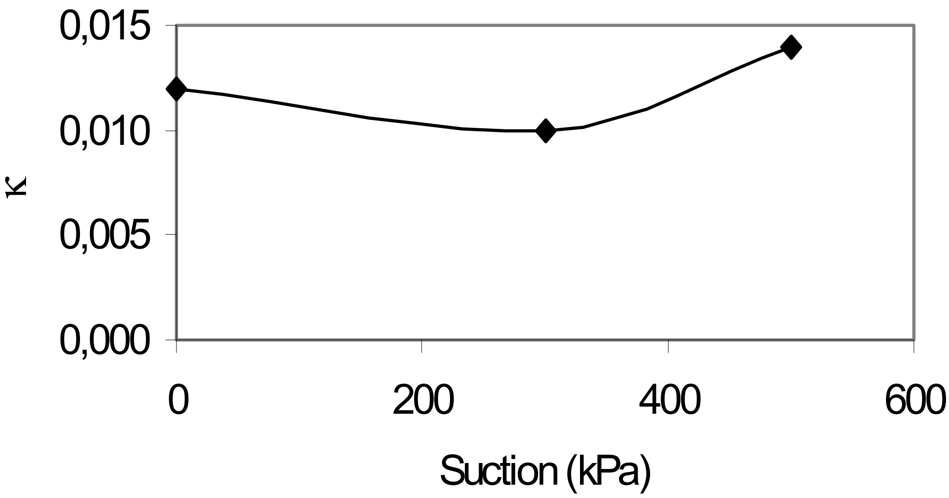

Figure 10. Variation of the elastic parameter with suction
Key : κ = slope of the unloading-reloading line in the $p : \upsilon$ space (critical state theory)

In figure 11, it was observed that change of suction from zero to 100 kPa increased the strength of Sainte-Rosalie clay by 70 kPa. This was an important strength increase for a 100 kPa suction increase. This measured strength increase explains what was usually observed in the field: Sainte-Rosalie clay is very compressible under wet conditions, although it is a very stiff material under dry conditions. The important strength gain observed upon soil drying may also be explained by the matrix suction effect. An additional parameter that increased the soil strength was probably organic matter oxidation which occurred during soil drying.
Figure 11 shows that the plastic parameter (λ) at suction zero is not actually different from the plastic parameter at suction 100 kPa (respectively 0.14 and 0.15). Previous experimental results show that λ decreased with increasing suction (Alonso et al., 1990; Cui and Delage, 1996; Wheeler and Sivakumar, 1995). A closer look at these results shows that the suction difference between tests which are compared is at least 200 kPa. The results of the two K_0 tests carried out in this experimental program may suggest that a change of suction which is less than 200 kPa is not significant enough to induce a change in soil compressibility.
In figure 11, one dimensional compression (performed at suction 35 kPa with gravimetric water content equal to 25%) is plotted together with the two K_0 tests performed at suctions 0 and 100 kPa. The yield stress at 35 kPa suction (one-dimensional compression) is greater than the yield stress at suction 100 kPa (K_0 test), which is contrary to the trend observed during this experimental program. This puzzling fact is explained by the procedure used to determine the yield stress. The Casagrande method used in determining the yield stress is closely related to the compressibility index (λ). In one-dimensional compression (35 kPa suction), λ is equal to 0.16 while the plastic parameter λ is equal to 0.14 in K_0 test at suction 100 kPa. This difference in λ values explains why the Casagrande method used in determining yield stress in the two tests provided a greater value for yield stress of one-dimensional compression although this latter test was carried out at a lower suction. This observation brings up the remark that soil yield stress may depend on the type of test performed.

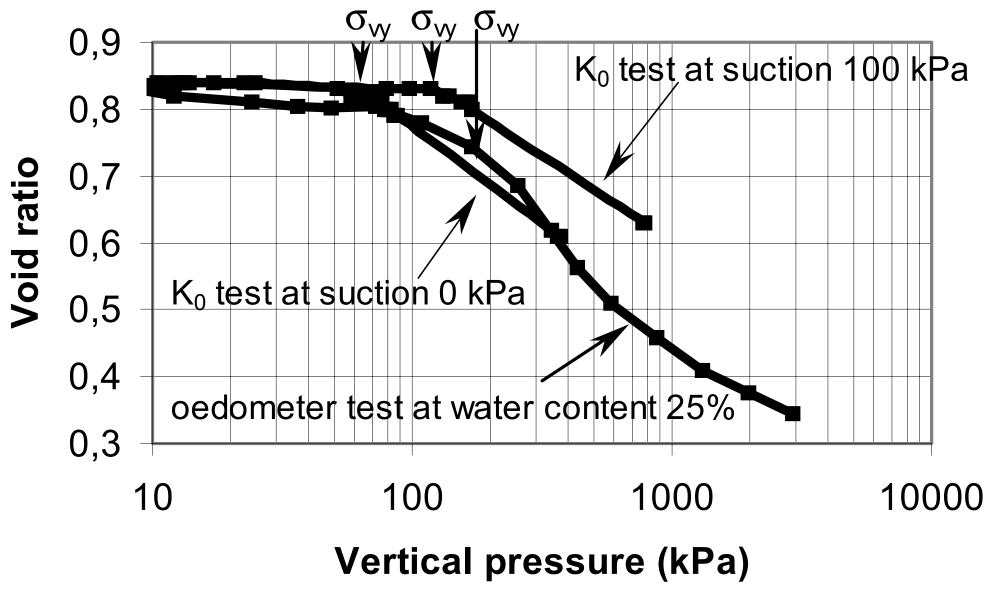

Figure 11. Coupled K_0 tests and one oedometer test performed on Sainte-Rosalie clay

Key: σ_{vy} = vertical yield stress

CONCLUSION

The total stress approach has been considered as valid for dealing with agricultural soil compaction problems. It has been very useful in conceptualizing the mechanical behavior of agricultural soils since it helped represent successfully agricultural soil behavior within the critical state framework. However, it seems today to be more appropriate to represent agricultural soil behavior through the stress state variables; this tool is efficient and more appropriate in analyzing unsaturated soil behavior as demonstrated by research in geotechnical engineering. Much research still needs to be done to adapt this approach to the particular case of agricultural soils. However, some tests can already be undertaken to determine whether this approach is useful for agriculture. The work presented in this paper has been conducted for this purpose. It shows that the concept of stress state variables can be used in analyzing the mechanical behavior of an agricultural soil. The analysis performed using this approach shows that:

1. the plastic parameter λ increased with water content up to the suction corresponding to optimum water content then decreased,
2. the elastic parameter κ did not vary as much as the plastic parameter λ , however, it decreased with increasing water content down to the suction corresponding to the optimum water content then increased, and
3. a small suction increase dramatically increased strength of Sainte-Rosalie clay. This fact was illustrated by K_0 tests run on Sainte-Rosalie clay under saturated condition and suction of 100 kPa. The K_0 test results showed that there is a strength gain of 70 kPa for 100 kPa suction increase. This significant strength gain is observed in the field where Sainte-Rosalie clay displays a high compressibility under wet conditions whereas it is very stiff under dry conditions.

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