Effects of Stresses and Time on Yielding of Clays

Effets du Temps et des Contraintes sur l'Etat Limité des Argiles

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SYNOPSIS. A laboratory investigation on Champlain clay from a test site in St-Alban, Quebec, was conducted to determine its characteristics at yielding. It is shown that the yield locus assumes an elliptical shape centered on the K_0 consolidation stress condition and that the position of this locus in the stress space is governed by the magnitude of the preconsolidation pressure. From results obtained at different depths and different sites it appears that the yield locus of a clay at a given depth is entirely determined by the knowledge of the corresponding values of ϕ' and P_c. The known effects of aging and strain rate on P_c are shown to be applicable to the entire yield locus.

As a result a general model for the behaviour of Champlain clays is proposed and its implications are discussed for such common practical problems as the interpretation and comparison of laboratory or in situ tests, the analysis of stability and settlement of embankments, the analysis of slope stability. Finally, the relevance of the concept of cementation bonds is discussed.

INTRODUCTION

The behaviour of Champlain clays (also referred to as Leda clays) has been a problem of major interest to Canadian researchers. The possible applicability to these sensitive clays of the concepts of yielding, developed at Cambridge, has been suggested by a few researchers since 1970 but a full understanding of these concepts and their implications has still to be developed. In particular the effects of the anisotropic initial consolidation and of the aging of natural clays, as well as the influence of loading rate or duration on the characteristics of the yielding of undisturbed sensitive clays need to be clarified.

Based on the laboratory investigation of the St-Alban clays, the purpose of this paper is to show that the concepts of limit state and critical state can be used to fully understand the origin and the characteristics of the behaviour of Champlain clays if such concepts are combined with Bjerrum's ideas on aging and time effects (Bjerrum, 1973), and to propose a general model for the behaviour of Champlain clays.

PROPERTIES OF THE CLAYS INVESTIGATED

The Champlain clay deposits in the St-Lawrence lowland and the Ottawa valley have been formed during the northerly recession of the Wisconsin ice sheet between 12,000 and 8,000 years before present. Even though they all carry the same name, it is admitted that the nature, deposition environment and resulting properties of these clay deposits vary with their location. The present investigation was initially concentrated on the St-Alban clay, which is a recent Champlain sea shoreline deposit 80 km west of Quebec City. In order to generalize the results, clays from three other sites, Ottawa, St-Louis and St-Vallier (Fig.1), have also been considered to provide a wide sample of Champlain clays from geographical, geological and mechanical points of view.

Small diameter tube sampling has been known to adversely affect the mechanical properties of Champlain clays. To avoid this problem all tests reported in this paper have been carried out either on block samples (Ottawa, St-Louis, St-Vallier) or on 20 cm diameter samples (St-Alban) obtained by using a new tube sampler developed at Laval University (Sarrailh,1975) and proven to yield samples equivalent to blocks in quality.

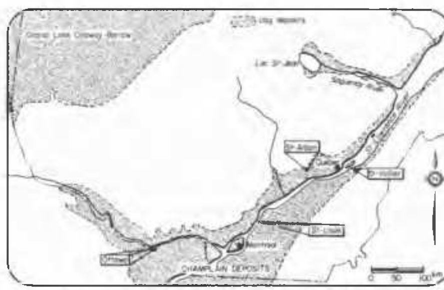

Fig.1 Location of Investigated Clay Deposits

The typical geotechnical properties of the clays investigated are summarized on table I. The St-Alban clay is a shoreline deposit of low plasticity, low porewater salinity and medium to high sensitivity. While

	St-Alban,3m (1)	St-Alban,5.7m (1)	Ottawa (2)	St-Louis (3)	St-Vallier (3)
Water content,(%)	90	60	65	69	59
Liquid limit, (%)	50	40	60	50	60
Plastic limit, (%)	27	23	24	27	23
Plasticity index, (%)	23	17	36	23	37
Clay content, (%)	81	45	68	78	65
C_u vane / P'_o	0.65	0.51	≃1.30	0.60	0.58
P_c oed / P'_o	2.25	2.10	≃4.30	2.20	2.50
Sensitivity by field vane	14	22	16 to 20	12	7
by laboratory vane				50	20
Salt content of the pore water, (g/l)	0.7	0.3	0.3 to 0.5	0.4	4

(1) Tavenas et Al,1974 (2) Mitchell & Wong,1973 (3) Lo and Morin,1972

Table I Typical Properties of the Clays Investigated it has not been submitted to any significant geological preconsolidation, this clay has developed a very high quasi-preconsolidation due to aging, as indicated by a nearly constant value of 2.1 to 2.3 of the overconsolidation ratio over the full depth of the deposit The Ottawa clay investigated by Mitchell and Wong (1973) has a much higher plasticity, a similar salinity and sensitivity. It has also certainly been submitted to an important geological preconsolidation as indicated by a P_c/P_o ratio of about 4.3. The St-Louis clay, investigated by Lo and Morin (1972) and in the present study, is possibly a brackish water deposit of low plasticity, low salinity and medium sensitivity. It has been submitted to a known geological preconsolidation and has apparently developed little quasi-preconsolidation to result in an overconsolidation ratio in the order of 2.2. The St-Vallier clay, investigated by Lo and Morin (1972) was deposited in a marine environment and is characterized by a high plasticity, a high salinity and a low to medium sensitivity. While it has been submitted to a known geological preconsolidation pressure, it has also developed some quasi preconsolidation to result in a P_c/P_o ratio in the order of 2.5. All clays are likely to have been submitted to leaching since groundwater gradients have been observed at the sampling locations.

EXPERIMENTAL DETERMINATION OF THE YIELD LOCUS

Samples obtained at 3 m and 5.7 m depth in the St-Alban clay deposit have been used in the present investigation. Each 20 cm diameter tube sample yielded 3 slices, 12.5 cm in height; in each slice, 7 specimen 3.8 cm in diameter could be cut so that a complete set of yield points could be obtained in the same sample. In this way the scattering of results due to the natural variability of the clay could be reduced to a minimum. At each depth, the complete limit state and critical state curves were obtained by means of at least 7 CIU tests, confirmed by 2 to 4 CID tests, and by means of σ_3'/σ_1' = Cst triaxial consolidation tests performed on 3.8 cm diameter samples. In addition, standard oedometer tests were carried out to determine the preconsolidation pressure. The same test program was carried out at the two depths in St-Alban.

Shear tests— The CIU tests were consolidated to stresses varying from 4 to 140 KN/m^2. A strain rate of 0.5% per hour was used for all tests. Figure 2

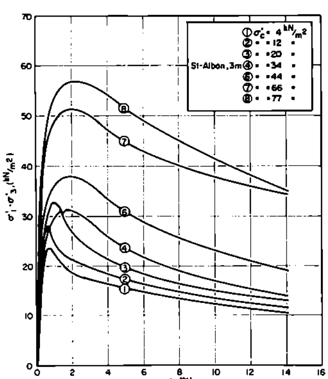

Fig.2 Stress-strain Curves in CIU Tests St-Alban 3 m

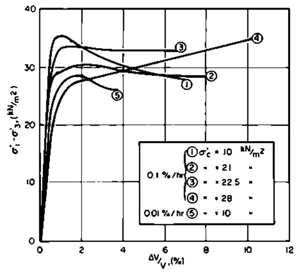

Fig.3 Stress-Volumetric Strain Curves in CID Tests St-Alban 3 m

shows the stress-strain curves for the specimen from 3 m depth; they are typical of Champlain clays. At low consolidation pressures (tests no.1,2,3) a peak strength is obtained at very low strain (0.5 to 1.0%) and a marked strain-softening occurs after the peak. At higher consolidation pressures, the peak is less pronounced and occurs at strains in the order of 2%. The CID tests were carried out at a strain rate of 0.1 % per hour. However in test no.5, the rate was reduced to .01% per hour. Figure 3 shows the stress-volumetric strain curves for the specimen from 3 m depth. Again here the behaviour is typical of Champlain clays with a peak strength and strain softening for the tests at low confining pressure σ_c', an elasto-plastic behaviour at intermediate σ_c', and a strain hardening behaviour at higher σ_c'.

The effective stress paths of the CIU and CID tests on specimen from 3 m depth are shown on figure 4, together with the envelope of the peak strengths. In the normally consolidated range, i.e. for consolidation pressures in excess of 22 KN/m^2, the envelope of peak strengths is linear, corresponding to a Mohr-Coulomb criterion with c' ≈ 0 and $\phi' = 27°$. In the overconsolidated range, the peak strength envelope is located well above the $\phi' = 27°$ line, as usual with Champlain clays. The results of CID tests (Fig.3) indicate that this peak envelope is actually a section of the locus of volumetric yield of the clay. The stress paths at large strains for all CIU tests appear to tend towards a unique envelope, corresponding to the critical state line of the St-Alban clay. This line could be defined by c_r' = 3 KN/m^2 and $\phi_r' = 27°$, but the exact magnitude of c_r' is difficult to assess since the strength corrections for membrane and filter papers at large strains are in the same order of magnitude as the measured c_r'.

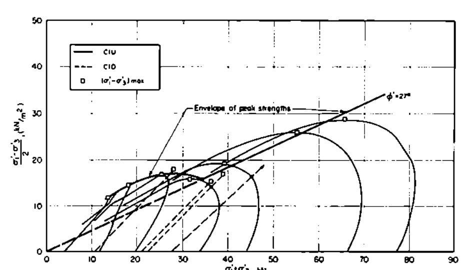

Fig.4 Stress Paths and Strength Envelope St-Alban 3 m

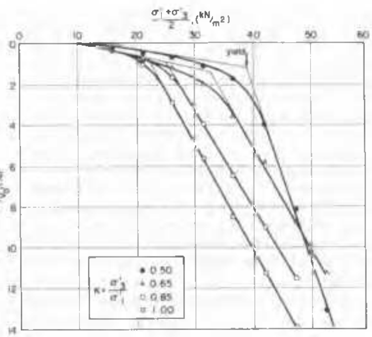

Fig.5 Volume changes in K = Cst Consolidation Tests St-Alban 3 m

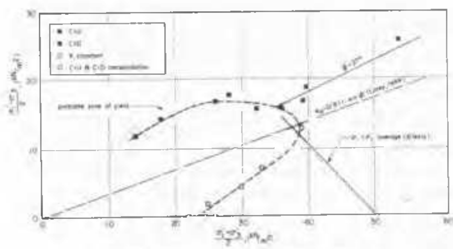

Fig.6 Yield Locus - St-Alban 3 m

Consolidation tests– To obtain the shape of the locus of volumetric yield at low shear stresses, series of triaxial consolidation tests at $\sigma_3'/\sigma_1' = C^{st}$ were carried out. The stresses were applied in steps lasting 24 hours. Figure 5 shows the volumetric strains as a function of $(\sigma_1'+\sigma_3')/2$ for four tests on specimens from 3 m depth. The volumetric yield points are clearly defined in all cases, and the corresponding yield stress conditions are represented on figure 6. The yield stress for K = 1.0 agrees well with that obtained from the consolidation of the different CIU and CID tests.

A further point on the yield locus is represented by the preconsolidation pressure in the oedometer test. Series of standard oedometer tests were carried out, with load increments of 50% maintained for 24 hours. At 3 m depth the average value of P_c from 6 tests was found equal to 50 KN/m^2. Since the exact value of the lateral stress in the oedometer is not known, the exact position of the yield stress condition corresponding to P_c in figure 6 cannot be defined but is known to be on the $\sigma_1' = P_c$ line. This line touches the yield locus very close to the K_o condition.

Shape of the yield locus– The stress conditions corresponding to volumetric yield of the clay from 3.0 m depth are shown on figure 6. As can be seen, the yield points from both shear and consolidation tests are on a continuous line confirming that the same phenomenon governs the behaviour of the clay in these two types of tests. However, the shape of this experimental yield locus strongly differs from the theoretical shape of the yield locus in the Cam-clay models. In particular, if the yield locus appears to have a more or less elliptical shape, this ellipse is not centered on the isotropic line but rather on a line close to the K_o line of the normally consolidated clay, the intersection of the yield locus with the K_o line corresponding roughly with the preconsolidation state of stress.

The experimental yield loci of the St-Alban clay from 3.0 and 5.7 m depth and of the Ottawa clay investigated by Mitchell and Wong (1973) are shown in figure 7. All three clays have the same effective friction angle $\phi' = 27°$ in the normally consolidated range. Their respective yield loci all have the same elliptical shape, centered on the K_o line corresponding to $\phi' = 27°$, but the position of the yield loci varies depending on the magnitude of the preconsolidation pressure in these three clays.

These findings are consistent with the concepts of the Cam-clay model but not with the details of that model. The main differences come from the fact that the Cam-clay model has been developed and is applicable for isotropic materials for which the yield locus is centered on the isotropic stress axis. In natural clays, deposition and preconsolidation develop under anisotropic stress conditions, and it has been shown by Salah Abdelhamid and Krizek (1976) that a constant effective stress ratio prevails during the early stages of a clay deposit. The theoretical value of $K_o = [(1+2/3 \sin\phi')/(1+\sin\phi')](1-\sin\phi')$ proposed by Jaky (1944) appears to give a good approximation of the stress ratio during consolidation. As a consequence the clay structure is organized anisotropically and it is logical to admit that the stress conditions causing volumetric yield of that structure should be refered to the K_o condition,

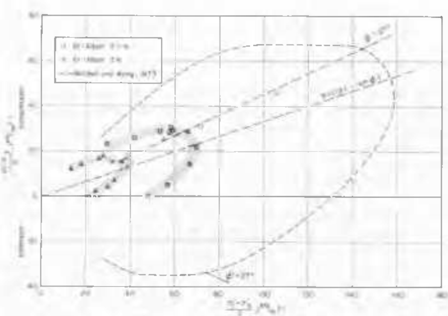

Fig.7 Yield Loci - St-Alban 3 m and 5.7 m and Ottawa

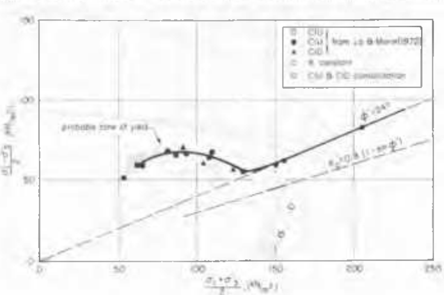

Fig.8 Yield Locus - St-Louis

and thus that the yield locus of a natural clay should be centered on the K_o line (Ohta and Hata, 1971). The position of this yield locus is governed only by the magnitude of P_c and the corresponding void ratio of the clay. Thus the yield locus of a natural clay is completely determined by its friction angle ϕ', which governs the K_o stress condition during deposition, and by its preconsolidation state of stress. Consequently, for a given clay material and ϕ' value, the yield loci at different depths (and thus different P_c) should all be homothetic, the increases in strength for example, being proportional to the increase in P_c. This is supported by the well admitted fact proposed by Bjerrum (1973) that C_u/P_o in normally consolidated clays, or C_u/P_c in overconsolidated clays is a constant depending only on the PI (and thus the ϕ') of the clay.

These observations are confirmed by the results on the St-Louis clay reported by Lo and Morin (1972). This clay has an effective friction angle of $\phi' = 24°$ and thus a higher value of K_o than the St-Alban or the Ottawa clay. Figure 8 presents the stress conditions corresponding to yielding, in CIU and CID tests reported by Lo and Morin (1972), as well as in $K = C^{st}$ triaxial consolidation tests performed in the present investigation. Again here, the yield locus seems to be centered on the K_o line but its elliptic shape is somewhat more round, owing to the smaller ϕ' and the resulting higher K_o values.

EFFECTS OF TIME ON THE YIELD LOCUS

It has been shown that the magnitude of the preconsolidation pressure governs the position of the yield locus in Champlain clays. Consequently, it is likely that all factors affecting P_c should have an influence on the entire yield locus. Furthermore, if the yield loci at different P_c are truly homothetic, as they seem to be, the effects on various points of the yield loci, and in particular on the shear strength of the clay should be proportional to the effects on P_c.

Effect of aging of natural clays– Bjerrum (1967) has shown that aging of clays under constant effective stresses causes a reduction in void ratio due to secondary deformations and that this reduction in void ratio results in an increase of the apparent preconsolidation pressure. Bjerrum (1973) also indicated that this effect was more pronounced, the more plastic the clay and he presented experimental results in terms of P_c/P_o curves for young and aged clays of different plasticity to support his statement. Figure 9 shows the C_u/P_o curve for the aged clay obtained by combining Bjerrum's well known C_u/P_o and P_c/P_o curves for aged clays. As can be seen the C_u/P_c "aged" curve is nearly identical to the C_u/P_o "young" curve, thus indicating that the increase in strength caused by aging is proportional to the increase in P_c. More generally, and as suggested by Burland (1971), it appears that aging would cause not only an increase in P_c but also an homothetic displacement of the entire yield locus of the clay. A question which remains unanswered is wether the secondary consolidation occurs at constant stress ratio K_o or not; no reliable experimental data are available on this particular problem. However, considering the present shape of the yield loci in the St-Alban clay which is known to have developed its quasi-preconsolidation only from aging, it would appear that the assumption of a constant K_o during aging could be acceptable since the yield loci are well centered on the K_o line of the normally consolidated young St-Alban clay.

Effects of rate or duration of loading– Crawford (1964) and Bjerrum (1967) have both demonstrated that the apparent preconsolidation of a clay is reduced if the rate of loading is reduced in the oedometer test and Bjerrum has shown that this effect was actually another materialization of the secondary consolidation phenomenon causing the above mentioned aging effect. Therefore, and for the same reasons as previously stated, a reduction in the rate of loading or an increase in the duration of load application should result in a reduction, not only of P_c, but of the entire yield locus.

In order to verify this point, 9 special oedometer tests were performed on the St-Alban clay from 3.0 m depth. Samples were first reconsolidated to the in situ effective overburden pressure and were then loaded in one step to loads of 28, 40, 45, 50, 54, 58, 63, 75 and 98 KN/m^2; the loads were left for 100,000 minutes and the settlements measured at different times. The load settlement curves observed after 1,000 minutes, 10,000 minutes and 100,000 minutes are shown on figure 10; the apparent over-consolidation pressures are reduced from 52 to 44 KN/m^2 as the duration of the load application increases from 1,000 to 100,000 minutes, thus confirming the significant influence of time on P_c. Isotropic consolidation tests were also carried out in the triaxial cell. A sample was loaded to about 50 KN/m^2 in steps of 5.5 KN/m^2 maintained for 5 days. From the volumetric deformations measured in the first 24 hours and after the full duration of each step, two $\Delta V/V$ vs pressure curves could be obtained, giving values of the isotropic consolidation of 25.5 and 22 KN/m^2 for 1 day and 5 days load duration respectively. Finally, as already

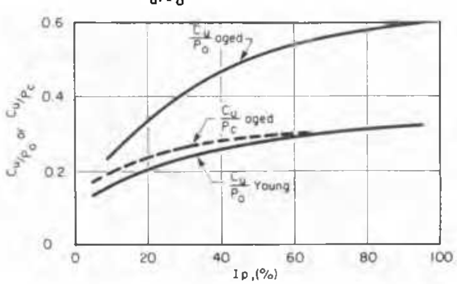

Fig.9 C_u/p for Young and Aged Clays After Bjerrum (1973)

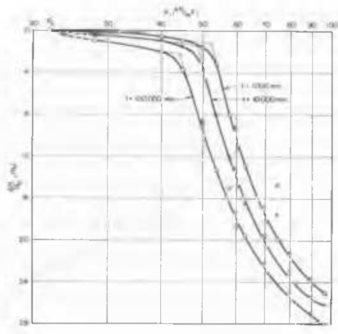

Fig.10 Effect of Time on P_c in Oedometer Tests St-Alban 3 m

indicated, CID tests consolidated at the same mean stress of 10 KN/m^2 were sheared at rates of 0.1 and 0.01% per hour. The reduction in strength with the strain rate is shown on figure 3: a peak strength of 18 KN/m^2 was obtained after 0.5 day in the fast test, as compared to a peak strength of 14 KN/m^2 obtained after 8 days in the slow test.

The results of the three types of tests are presented on figure 11 along with the yield locus obtained from standard tests. The displacement of the yield locus towards reduced preconsolidation pressures and shear strengths is obvious. The magnitude of this displacement appears to be relatively uniform for all points of the yield locus, but additional experimental data would be required to verify if this displacement is homothetic as this was suggested to be the case for the aging effect.

Similar time effects have been observed by Lo and Morin (1972) in the St-Vallier clay, which, as already noted, has been preconsolidated geologically. The results presented on figure 12, indicate that the displacement of the strength envelope due to changes in the strain rate is important and more or less homothetic.

MODEL OF THE BEHAVIOUR OF CHAMPLAIN CLAYS

Based on the experimental evidence presented herein it is possible to combine the basic principles of limit and critical state proposed by Roscoe and his co-workers and the findings of Bjerrum on the effects of aging and strain rates to obtain a conceptual model for the behaviour of natural Champlain clays.

When Champlain clays were deposited, their mineralogy and their deposition environment imposed the magnitude of their effective friction angle ϕ' and the type of e-log p relationship. As deposition continued the clay was submitted to increasing overburden pressures p and to corresponding horizontal stresses K_0p. During this process the void ratio decreased according to the e-log p relationship and a corresponding yield locus developed which was centered on the K_0 line in the stress space. At the end of deposition, point B in figure 13, the void ratio was e_B and the corresponding yield locus was Y_0 passing through point B on the K_0 line. With the developement of secondary consolidation during aging of the deposit, over say 10,000 years, the void ratio was reduced to e_A at constant overburden pressure P_B (point B'), resulting in an apparent preconsolidation pressure P_C (point C) and in a corresponding yield locus Y_1 for a 1 day loading rate. If some erosion has taken place during this process the present overburden pressure will be P_A corresponding

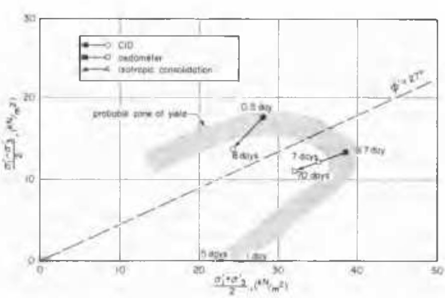

Fig.11 Effects of Time on the Yield Locus St-Alban 3 m

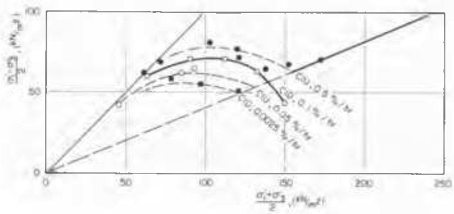

Fig.12 Effects of Time on the Strength St-Vallier (after Lo & Morin 1972)

to point A in figure 13. The behaviour of the clay presently submitted to condition A can now be completely described on figure 13(a).

If the clay is submitted to stress conditions in zone I, failure will occur immediately when the applied stresses correspond to points on the upper part of the yield locus Y_1, left of point α, or to points on the Mohr-Coulomb line right of point α.

If stress conditions corresponding to zone II are applied, large consolidation deformations will develop as soon as the stress path crosses the Y_1 yield locus below point α. This is for example what happens in the oedometer test when the applied stress exceeds P_C. Failure will not occur if the stress conditions remain below the ϕ' line.

If the applied stresses correspond to a point in zone III, between the "young" Y_0 and "aged" Y_1 yield loci below the ϕ' line, the clay will develop secondary volumetric deformations at a rate which will depend on the position of the applied stress condition relative to Y_1 and Y_0: close to Y_1 the rate of deformation will be high; close to Y_0 the rate will be extremely small, corresponding to the present own rate of secondary consolidation of the clay. Here also, no failure would develop since the stress conditions would be below the ϕ' line.

If the clay is now submitted to stresses below the immediate yield locus Y_1, in zone IV, it will remain stable first, but creep deformations will develop. With the passing of time, as shown in figure 11 and 12, the apparent yield locus will move from Y_1 towards Y_0 and will therefore pass through the applied stress condition after some time, the magnitude of which will depend on the position of the applied stress condition relative to Y_1 and Y_0; when this occurs, the clay will fail in an apparent creep failure.

Finally, for applied stress conditions within the Y_0 yield locus in zone V, no failure will ever occur, even for stress conditions above the ϕ' line. The Y_0 yield locus thus represents the lower strength limit of this clay.

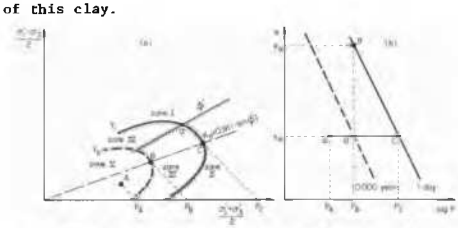

Fig.13 Proposed Model for the Behaviour of Clays

It should be emphasized that a separate set of Y_0-Y_1 yield loci exists at each depth, i.e. for each eA value in a deposit consisting of homogeneous clay with a given ϕ'.

EVALUATION OF PRESENT PRACTICES USING THE PROPOSED MODEL

In addition to helping in the understanding of the origin and characteristics of clay behaviour, the proposed model also provides a rational basis for the evaluation of some important aspects of the present practice of clay mechanics.

Interpretation of laboratory and in situ tests— A wide variety of tests is being used for the determination of the strength of undisturbed clays. It has been a common practice to evaluate the quality of these tests by comparing the magnitudes of measured strengths, admitting implicitely that the best test was the one giving the highest strength.

It was shown that the structural strength of an undisturbed clay with an initial void ratio e, (assuming negligeable variations of e within the elastic limit of the clay) is represented by its yield locus with a curved shape in the σ'_v, σ'_{h1}=σ'_{h2} plane. The CIU test results (Fig.3) also indicated that the critical state corresponding to the initial void ratio e_o was not located on the yield locus. Therefore the magnitude of the maximum strength measured in any test will, for a given clay at a given depth, be different from the critical state and will thus depend on the effective stress path followed during that test and on the resulting point at which this stress path reaches the yield locus corresponding to this clay and depth. This should be true for all clays with a strain-softening characteristics. For example, UU tests carried out at very low mean effective stresses will give relatively low undrained shear strengths. On the other hand, CIU or CAU tests reconsolidated to the in situ stress conditions correspond to stress paths reaching the yield locus closer to the point of maximum shear strength and will thus give higher strengths.

In the three dimensional stress space, the shape of the yield locus is not clearly known but it is not simple (Mitchell & Wong, 1973). However, the same principle applies, that the strength measured depends on the stress path along which it is measured. Thus, plane strain laboratory tests should give their own value of C_u. Similarly, in situ pressuremeter tests carried out at σv=C^{st} follow an unusual stress path and should give a value of C_u on the yield locus at a point which is difficult to locate in the effective stress space, but certainly different from those corresponding to other classical tests. Static cone penetration tests, or vane shear tests, are also likely to give a particular value of C_u but they are impossible to interpret correctly since the effective stress paths followed up to failure in these tests are not known.

A first consequence is that each test gives a different magnitude of the shear strength of a given clay, the result being related to the effective stress path of each test. The compared magnitude of the measured strength is thus no indication of the quality of the different tests, all results being simply a different picture of one and the same yield locus of the clay investigated.

A second consequence is that the strength measured in any test, while reprentative of the yield locus of the clay, is only then applicable to the analysis of a given practical problem if the stress paths in the test and in the problem are similar. For example there is no reason why the strength measured in a UU test should be directly applicable to the analysis of the stability of an embankment since the two stress paths are significantly different; on the other hand the stress paths followed in an in situ pressuremeter test and in front of an horizontally loaded pile are very similar and the strength obtained from the test should be identical to that mobilized around the pile. Finally, it has been shown that, for a given clay with known values of ϕ' and P_c, the yield locus is well defined in shape and position in the stress space. While the strengths measured in different tests or mobilized in situ will generally differ from each other due to the differences in the stress paths followed, the fixed shape of the yield locus imposes that a constant ratio will exist between the strengths measured in different tests: for example in St-Alban and St-Louis, the strength from CIU tests is generally equal to 1.5 times the UU strength; also, constant values of the R_p/P_L ratio are known to exist in uniform clay deposits; the constant C_u/P_c ratios proposed by Bjerrum are a further example. Similarly, a constant ratio should also exist between the strength obtained from a given test and that mobilized in a structure: the magnitude of this ratio will depend strictly on the differences in the stress paths followed in the test and the structure, and will generally be different from 1.0. Since it appears difficult to develop tests simulating properly the stress paths for each possible structure, it is more appropriate to refer to a simple test and determine empirically the strength ratio for each type of structure; Bjerrum's vane correction factors proposed in 1973 are typical of this approach.

Analysis of embankment stability— The stability of embankments on soft clays is generally based on a ϕ = 0 analysis using the vane shear strength and eventually applying the strength correction proposed by Bjerrum (1973). While this method has proven satisfactory in practice for single stage constructions, it has already shown some limitations.

The construction of an embankemnt results in increases of all components of the stress field as well as in principal axes rotation. The total stress paths followed, at least initially, correspond to significant increases in mean normal stress for limited increases in shear stress. Experience also shows that the pore pressures generated are initially low resulting in important increases of the mean normal effective stress. Thus the effective stress paths during construction are located well below the ϕ' line and, with continuing construction, reach the yield locus corresponding to the field rate of load application, below the ϕ' line. When this occurs, in undrained conditions, pore pressures are generated to maintain the effective stresses on the yield locus which then becomes the mandatory effective stress path (Burland, 1971). The construction behaviour of the three test embankments in St-Alban gives a direct confirmation of this, as shown on figure 14. If construction continues, the effective stress path will follow the yield locus until the Mohr-Coulomb envelope of the normally consolidated material, characterized by c', ϕ', is reached, at which point failure will develop in the clay foundation. This mechanism implies that in most practical cases, and in particular when construction pore pressures are low initially, the stability of embankment foundations is governed, not by the undrained shear strength of the undisturbed clay, but rather by the effective strength parameters of the normally consolidated clay, c', ϕ'. Proper stability evaluations should thus be based on an effective stress analysis, particularly when stage construction is used.

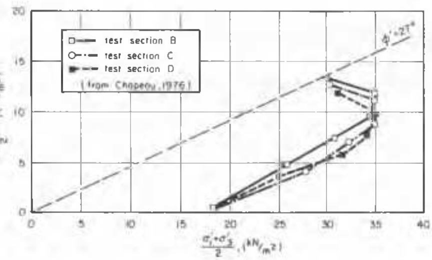

Fig.14 Effective Stress Paths Under 3 Test Embankments - St-Alban

Slope stability analysis— During the excavation or the erosion of a slope, the mean normal stresses are reduced as the shear stresses increase. In the slope, at each depth the clay has been submitted to a specific stress history and has developed a corresponding set of yield loci Y_1-Y_0 (ref. to figure 13). In the initial stages of excavation or erosion the stress conditions correspond to zone V of elastic behaviour.When excavation continues the shear stresses increase and, at any depth, failure will occur when the local stress path reaches the yield locus Y corresponding to the age of the slope, Y_0 being the lowest possible position of Y for an age of slope equal to the age of the deposit. Thus the strength mobilized at failure in the slope should be the envelope of the points of intersection of the stress paths at each depth with the local yield loci Y. This envelope is necessarily different in nature and characteristics from the effective stress envelope determined by any tests on samples from a given depth in the slope.

Other applications— The proposed model can be used to analyse qualitatively and eventually quantitatively most problems involving soft clays. For example it sheds some new light on the analyses of settlements, in as much as the pre-consolidation pressure obtained from oedometer tests may not be applicable to the condition prevailing below certain types of structures due to differences in the stress paths of the oedometer test and the structures. Mc Rostie, Burn and Mitchell (1972) have shown how the peculiar shape of the yield locus of an Ottawa clay has caused serious consolidation deformations due to induced moderate horizontal pressures behind a tied-back wall. The proposed model may also be used in analysing the behaviour of piles in clays. In particular it justifies the use of an effective stress approach for the evaluation of the point resistance and skin friction mobilized during pile loading: due to the remolding caused by pile driving, the clay around and under the pile has developed a new yield locus corresponding to the stress conditions resulting from driving and it is in a normally consolidated state at these stress conditions. The loading of the pile will result in effective stress paths coincident with the new yield locus and failure will occur when the Mohr-Coulomb line c', ϕ' of the normally consolidated clay is reached.

The model also provides a more rational basis for the analysis of creep phenomena, which may occur in nature under a wide variety of stress states, while the present practice of using stress levels refered to a unique shear strength as basic parameter provides information on the creep behaviour along only one stress path.

The model may also be used to reassess the validity of the concept of cementation of Champlain clays. It should be noted that the concepts of yielding, aging, etc. which were shown to apply to Champlain clays, were initially developed on artificial or natural clays reputedly uncemented. Also, some of the characterestics which were attributed to cementation, such as the curved shape of the strength envelope, might be due to normal effects of anisotropic over-consolidation. Thus it appears that the behaviour of Champlain clays is, in many ways, similar to that of any overconsolidated clay, so that the relevance of the concept of cementation needs serious reexamination.

CONCLUSION

From the present investigation on Champlain clays, the following main conclusions can be drawn.

1- The structural strength of any undisturbed Champlain clay is governed by the principles of yielding proposed by Roscoe and his co-workers. However, the shape and position of the yield locus in the stress space is different from the theoretical shape implied in the Cam-clay model. The yield locus of a natural clay has an elliptical shape, centered on the K_o line of the normally consolidated clay, and the position of the yield locus along that line is governed by the preconsolidation pressure. For a clay with a given effective friction angle ϕ', the yield loci at different depths and P_c are homothetic along the $K_o = 0.9\ (1 - \sin \phi')$ line of that clay.

2- The aging of a Champlain clay results not only in increases of P_c (Bjerrum, 1967) but also in homothetic variations fo all points of the corresponding yield locus. Inversely, a reduction in the rate of loading or an increase in the duration of load application results in a reduction of all points of the apparent yield locus.

3- A simple model for the behaviour of Champlain clays is proposed, which combines these effects of stress and time.

4- Using the proposed model the strength measured in any of the usual tests is shown to depend on the stress path followed in the test. It will thus be different from test to test as well as from the strength mobilized under a structure. However, constant ratios will exist between the strengths measured in specific tests or mobilized under various structures.

5- The proposed model is used to demonstrate the necessity of analysing the stability of embankment in terms of effective stresses rather than by means of a $\phi = 0$ analysis, to show some of the weaknesses of the present approach to the analysis of slope stability, or more generally, as a rational basis for the analysis of the mechanical behaviour of Champlain clays.

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REFERENCES

Bjerrum, L., 1967. "Engineering Geology of Normally Consolidated Marine Clays as Related to the Settlements of Buildings". Geotechnique 17(2), pp.83-119.

Bjerrum, L., 1973. "Problems of Soil Mechanics and Construction on Soft Clays and Structurally Unstable Soils (Collapsible, Expansive and Others)". State of the Art Report, Session 4, Proc. 8th Int. Conf. Soil Mech. Found. Eng., Moscow, Vol.3, pp.111-160.

Burland, J.B., 1971. "A Method for Estimating the Pore Pressures and Displacements Beneath Embankments on Soft, Natural Clay Deposits". Proc. Roscoe Mem.Symp. on Stress-Strain Behaviour of Soils. Foulis et Co., pp.505-536.

Chapeau, C., 1976. "Contribution à l'étude des tassements instantanés des remblais sur argiles sensibles Thèse de maîtrise, Université Laval, Québec, Canada.

Crawford, C.B., 1964. "Interpretation of the Consolidation Test". ASCE Journ. of Soil Mech. and Found. Div., Vol.90(SM5), pp.87-102.

Jaky, J., 1944. "A Nyugalmi nyomas tenyezöje" Magyar Mernök es Ëpitesz Közlönye, pp.355-358.

Lo, K.Y., Morin, J.P., 1972. "Strength Anisotropy and Time Effects of Two Sensitive Clays". Canadian Geo. Journ., Vol.9(3), pp.261-277.

Mc Rostie, G.C., Burn, K.N., Mitchell, R.J., 1972. "The Performance of Tied-Back Sheet Piling in Clay". Canadian Geotechnical Journ., Vol.9(2), pp.206-218.

Mitchell, R.J., Wong., K.K., 1973. "The Generalized Failure of an Ottawa Valley Champlain Sea Clay". Canadian Geotechnical Journ., Vol.lo(4), pp.607-616.

Ohta, H., Hata, S. 1971. "On the State Surface of Anisotropically Consolidated Clays". Proc. Japan Society of Civil Eng., No.196, pp.117-124.

Salah Abdelhamid M., Krizek, R.J., 1976. "At Rest Lateral Earth Pressure of a Consolidating Clay". ASCE, Vol.102(GT7), pp.721-738.

Sarrailh, J., 1975. "Contribution à l'étude des méthodes d'échantillonnage des argiles sensibles". Thèse de maîtrise, Université Laval, Québec.

Tavenas, F., Chapeau, C., La Rochelle, P., Roy, M., 1974. "Immediate Settlements of Three Test Embankments on Champlain Clay". Canadian Geotechnical Journal, Vol.11(1), pp.109-141.