THE UNIVERSITY OF MANITOBA

YIELDING CRITERIA AND LIMIT-STATE IN A WINNIPEG CLAY

by

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ABSTRACT

This thesis investigates the applicability of the concept of yielding to Lake Agassiz clay in the Winnipeg area. Careful sampling and laboratory testing techniques have been used. The test program was designed to examine the limit-state for the blue clay at 11.5 m depth. The study also investigated the time-dependent aspects of the YLIGHT model of soil behaviour, strain energy as a criterion for identifying limit-state, and the threshold energy concept at yielding.

Eighteen 76 mm diameter undisturbed triaxial samples were tested along various stress paths. Drained, stress-controlled tests show that yielding is controlled by the in-situ grain structure of the clay, and by stress-history effects. For the blue clay at 11.5 m depth, a well defined yield envelope has been identified which supports the YLIGHT model concept proposed for Champlain Sea clay. Yield envelopes from different depths in the Winnipeg clay are fairly homothetic, and can be normalized with respect to p'_c.

Undrained, strain-controlled portions of the triaxial testing program were used to examine several aspects of the clay's behaviour. On the basis of the $(\sigma_1-\sigma_3)/2_{max}$ failure criterion, the normally consolidated Coulomb-Mohr strength parameters, c' and ϕ' were found to be 4 kPa and 17.5^o respectively. The average value of s_u/p'_c was found to be 0.22. Porewater pressures at failure depend strongly on the stress levels and stress ratios during laboratory reconsolidation. Values of A_f range between 0.22 to 1.59. The relative stiffness, E_{50}/s_u, lies between 168 and 361. For a tenfold change in strain rate in Winnipeg clays, the change in undrained strength is approximately 11 to 12 percent.

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LIST OF SYMBOLS

a - area of loading piston in the triaxial cell

a_v - coefficient of compressibility

A, B - porewater pressure parameters (after Skempton, 1954)

A_f - value of A at failure

A_ε - instantaneous sample area

c' - effective cohesion intercept

C_c - compression index

c_v - coefficient of consolidation

CAD - stress-controlled, consolidated anisotropically drained test

CAD(U) - strain-controlled, undrained compression test with porewater pressure measurements preceded by CAD test

CAU - strain-controlled, consolidated anisotropically undrained compression test

CID - stress-controlled, consolidated isotropically drained test

CID(U) - strain-controlled, undrained compression test with porewater pressure measurements preceded by CID test

e - voids ratio

e_o - initial voids ratio

E_{50} - elastic modulus to 50% of failure stress

G.W.L - groundwater table or phreatic surface

G_s - specific gravity

I_p - plasticity index

k - coefficient of permeability

K_o - coefficient of earth pressure at rest

LSNV - Length of Strain Vector

LSSV - Length of Stress Vector

m_v - coefficient of volume change

OCR - overconsolidation ratio

p' - mean principal stress; $= (\sigma_1' + \sigma_2' + \sigma_3')/3$

p_c' - effective preconsolidation pressure

$(p_c')_{iso}$ - effective preconsolidation pressure in an isotropic compression test

p_o' - effective vertical overburden stress

$(p_{vert}')_{max}$ - maximum effective vertical overburden pressure (approximately equal to p_c')

q - principal stress different; $= (\sigma_1 - \sigma_3)$

s_u - undrained strength; $= (\sigma_1 - \sigma_3)/2_{max}$

u - porewater pressure

w - natural moisture content

w_L - liquid limit

w_p - plastic limit

W - strain energy absorbed per unit volume

W_o - dead load acting at mid-height of sample during consolidation

γ	- average unit weight
ε_1, ε_3	- major and minor principal strains (i.e. axial and radial strains in triaxial compression test)
ε_{1c}, ε_{3c}	- ε_1 and ε_3 at the end of triaxial consolidation to σ'_{1c}, σ'_{3c}
ε_v	- volumetric strain in triaxial compression test
ε_{vc}	- ε_v at the end of triaxial consolidation to σ'_{1c}, σ'_{3c}
ε_ρ	- average axial strain during relaxation test in undrained compression test
$\dot{\varepsilon}_1$	- axial strain rate
$\rho_{0.1}$	- strain rate effect parameter
σ'_1, σ'_3	- major and minor effective principal stresses
σ'_{1c}, σ'_{3c}	- σ'_1 and σ'_3 at the end of triaxial consolidation
σ'_h	- effective horizontal stress
σ_{oct}	- total octahedral normal stress
σ'_{oct}	- effective octahedral normal stress
σ'_{scalar}	- effective scalar stress
σ'_v	- effective vertical stress
ϕ'	- effective angle of shearing resistance

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CHAPTER 1

INTRODUCTION

Perhaps the most important technical development at the 1979 Canadian Geotechnical Conference was the considerable attention directed for the first time at these conferences to the concept of "yielding" as defined by a limit-state surface in stress space. The limit-state surface in a general stress space is a boundary, or "envelope", at which the compressibility, settlement rate and porewater pressures of undisturbed natural clay all increase markedly as stresses are increased from in-situ stresses to stresses associated with engineering construction. The distinction between limit-state and critical-state surfaces has been carefully examined by Noonan (1980).

Limit-state surfaces or yield envelopes, for post-glacial clays are currently receiving much research attention. Most studies have involved the marine clays of Eastern Canada, (see for example Mitchell, 1970; Tavenas and Leroueil, 1977). Limit-state studies were initiated by Dr. J. Graham in 1976 at the University of Manitoba to examine the applicability of the limit-state concept to the glaciolacustrine clays of Winnipeg area. The testing program consisted of 76 mm diameter samples, trimmed using equipment specially designed to minimize disturbance, and tested in large diameter, rotating-bush triaxial cells. Samples were taken from 6 m to 12 m depth at the University of Manitoba campus using the block sampler devised by Domaschuk (1977). Preliminary results were presented by Baracos et al.

(1980). Subsequently, further studies have been carried out by Noonan (1980). In concluding his thesis, Noonan drew attention to certain aspects of the clay behaviour which were still unclear. The more important of these may be summarized as follows:

1. Because of the limited number of samples tested, the shape and orientation of the yield envelopes[*] defined in the earlier tests were tentative. Hence, the details of the YLIGHT model (Tavenas and Leroueil, 1977) could not be confirmed.
2. Verification of the applicability of YLIGHT model to Winnipeg clays required further testing on a larger number of samples from one depth. Isotropic, effective stress paths should be included.
3. The effect of load duration and load increment ratio on the stress-strain time results were not investigated in the earlier tests. They were associated with the time-dependent aspects of YLIGHT model.

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[*] There is some confusion in the usage of the terms "Limit-State Envelope" and "yield envelope". Technically, it would appear that "Limit-State Envelope" should be restricted to the locus of yield points in a constant-e plane in (p', q, e) space, as defined for example by undrained tests (Roscoe and Burland, 1968). In contrast, the yield envelopes described in this thesis are derived from tests which start from the same initial p'_o, $K_o p'_o$, e_o - conditions, but have different voids ratios at yield. The yield envelopes therefore, although shown in Fig. 4.27 for example in (p', q) space, are not in a constant-e plane. The 3-dimensional envelope of the separate limit-state stresses (or yields) found from the individual tests is known as the Limit-State Surface.

4. Strain energy as a yielding criterion needed further investigation.
5. Four 63 mm diameter oedometer samples had been tested in the earlier tests, but there was considerable uncertainty regarding the variation with depth of the preconsolidation pressure p'_c.
6. The samples used in the earlier studies had been stored for more than a year during which time properties of the clay might have been altered significantly. It was suggested that the storage time of samples prior to testing be minimized in the future.

In response to these conclusions, it was considered necessary to carry out further testing, and block samples were taken on July, 1980 and January, 1981 from 11.28 m to 11.66 m depth at the same test site (Baracos et al., 1980). These have now been tested and the results are contained in this thesis. The specific aims of this thesis were as follows:

1. To improve the existing techniques for determining yield envelopes in Lake Agassiz clay.
2. To examine the influence of load duration and load increment ratio on the determination of the yield envelopes in plastic clay.
3. To examine the criteria for defining yield stresses from various stress-strain plots.
4. To investigate the validity of strain energy as a yield criterion and to examine if there is a threshold energy

for yielding which is stress path independent.

5. To improve the techniques for oedometer testing and to determine the distribution of p'_c with depth on the test site.
6. To study the effects of changes of strain rate on undrained shear strength.

The laboratory testing program which will be described in detail in a later chapter, consisted of eighteen large diameter (76 mm), triaxial tests, four oedometer tests and standard classification tests which include sensitivity tests. Both 63 mm and 76 mm diameter oedometer samples were used to determine p'_c. Data were obtained on both drained and undrained triaxial behaviour. Drained stress-controlled triaxial tests were used to examine the limit-state condition along various stress paths. The results were examined with reference to the YLIGHT model proposed by Tavenas and Leroueil (1977), and with regard to the use of different components of stress tensor to define the limit-state condition. In addition, strain energy as a yield criterion was investigated. Samples which were not stressed to rupture during the drained portion of the triaxial test were tested to failure in undrained shear. The undrained part of the test allowed examination of the following characteristics of clay behaviour: the influence of consolidation history on porewater pressure generation and elastic moduli; the effects of changes of strain rate on the undrained shear strength; and the normally consolidated Coulomb-Mohr rupture envelope. In addition, the results of one-dimensional oedometer tests were used to examine the drained compression behaviour of clays along the K_o -

consolidation line.

Before proceeding to the testing program (Chapter 3) and its results (Chapter 4 and 5), the thesis will present in Chapter 2 a brief review of the concept of yielding and the YLIGHT model proposed by Tavenas and Leroueil (1977); and the recent limit-state studies in Lake Agassiz clay (Baracos et al., 1980; Noonan, 1980).

CHAPTER 2

A REVIEW OF LIMIT STATE CONCEPT AS APPLIED TO THE LAKE AGASSIZ CLAYS

2.1 INTRODUCTION

In recent years, considerable attention has been paid to the geotechnical properties and behaviour of soft clays and sensitive clays. Much of the research has focussed on Norwegian quick clays, and on the cemented Leda clays found in Eastern Canada (Bjerrum, 1967; Townsend et al., 1969; Mitchell, 1970; Tavenas and Leroueil, 1977). Excellent reviews of the geotechnical properties and behaviour of the soft post-glacial clays in Canada with respect to embankment and foundation design have recently been presented by Quigley (1980), and by Kenney and Folkes (1979).

Various investigators have shown that the concepts of limit and critical states originally proposed by Roscoe, Schofield and Wroth (1958) and Roscoe and Burland (1968) to describe the behaviour of isotropically consolidated clays could be extended and modified to apply to natural, anisotropic clays. In particular, the existence of limit-state surfaces has been demonstrated by tests on intact lightly overconsolidated clay samples by Graham (1969), Mitchell (1970), Crooks and Graham (1976), and Tavenas and Leroueil (1977). In addition, Baracos et al. (1980) and Noonan (1980) have shown that yield envelopes can be defined in (p', q) stress space for the glacio-lacustrine clays of the Winnipeg area. The practical significance of the limit-state concept in understanding the behaviour of clay, and in the design of structures on clay foundations has been shown by Tavenas and Leroueil (1977); Tavenas et al. (1978b and 1979); and Tavenas (1979).

Noonan (1980) has given an extensive literature review of the concept of limit-state and critical-state. He discusses its initial development (Roscoe et al., 1958), and the present understanding it provides for the behaviour of natural clays (Tavenas and Leroueil, 1980). Prior to the work by Tavenas and his co-workers at Laval University, an overall picture of the nature of the limit-state envelope for a clay and the factors affecting it was not clear, although yield envelopes for various clays had been found (for example, Mitchell, 1970; Crooks and Graham, 1976).

The following two sections present briefly the YLIGHT model proposed by the Laval workers, and the factors which affect the determination of limit-state envelopes. In view of Noonan's recent review (1980), the presentation will be brief, and restricted to those aspects which relate to the testing program described in this thesis.

2.2 THE YLIGHT MODEL

Tavenas and Leroueil (1977) showed that the shape of the limit-state surface of a natural clay reflects the mineralogy of the deposit, and the stress anisotropy prevailing during deposition and consolidation. It is approximately symmetrical about the $K_o = 0.9 \times (1-\sin\phi')$ line (Jaky, 1944; Tavenas et al., 1977). Its position along the K_o - line, as well as its size, are fixed by local values of the preconsolidation pressure, p'_c. These results were also shown in preliminary reports by Graham (1969, 1974). On compiling the data available to them, Tavenas and Leroueil (1977) showed that all limit-state surfaces obtained on natural clays have these characteristics and are different from the theoretical shape implied in the Cam Clay model of soil behaviour (Roscoe and Burland, 1968). In addition, they showed that the effect of aging (i.e. the decrease of voids ratio of a clay with time at constant effective stresses due to secondary compression) and strain-rate described by Bjerrum (1967) can be accounted for in their behavioural model known as YLIGHT. This model was initially proposed for Champlain Sea clays (Tavenas and Leroueil, 1977). Its applicability to all natural clays appears promising and is presently being evaluated at the University of Manitoba using Lake Agassiz clay. Detailed examination of the model and the logic behind it have been presented by Noonan (1980). The important features of the YLIGHT model may be summarized as follows:

1. The limit-state envelope of a natural clay has a shape which is approximately elliptical, and centered on the K_o - consolidation line of the normally consolidated clay.
2. The position of the limit-state envelope in stress space is governed by the magnitude of the preconsolidation pressure, p'_c.
3. The limit-state envelope of a natural clay can be qualitatively determined by its effective friction angle, ϕ', which governs the K_o - stress condition of the normally consolidated clay; by its preconsolidation pressure; and by its undrained shear strength.

4. The limit-state envelope can be approximately located in stress space given knowledge of the parameters $(s_u)_{max}$*, $(p'_c)_{iso}$, $(p'_{vert})_{max}$, and the K_o - consolidation line (Fig. 2.1). (All figures are presented at the back of this thesis after the References and Tables). It is also noted that the ratio of $(p'_{vert})_{max}$ to $(p'_c)_{iso}$ is generally in the order of 1.4 to 1.8 (Leroueil and Tavenas, 1977).
5. In a uniform clay which has been deposited in a single unit, the limit-state envelopes at different depths, and thus different p'_c values, are all homothetic, that is, geometrically similar.
6. The critical state line, as used in the model, is identical to the large strain, normally consolidated Coulomb-Mohr strength envelope.
7. The effect of aging of natural clays, as well as the influence of longer loading duration or slower strain-rate can cause the entire limit-state envelope to shrink inwards with time (Tavenas et al., 1978b).

It should be noted that further testing is required to confirm the general validity of this model for all natural clays. In particular, the effect of aging of natural clay, and the influence of loading rate or duration on the characteristics of the yielding of undisturbed natural clays, need further investigation.

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*See List of Symbols on Page vi

2.3 FACTORS AFFECTING THE DETERMINATION OF YIELD ENVELOPES

A generally accepted definition for the yield envelope of a natural clay is a locus joining a set of yield points in the (p', q) stress space corresponding to the in-situ voids ratio e, inside which strain, strain rates, and porewater pressure generation are low; and outside which all of these parameters are much higher (Baracos et al., 1980; Noonan, 1980). States of stress inside this envelope produce a pseudo-elastic, relatively incompressible and largely recoverable response associated with small-strain, rapid, readjustment of the grain structure of the clay. Non-failing stress states which are outside the yield envelope, in (p', q) space, but on the limit-state surface in (p', q, e) space, produce a more compressible and irreversible response associated with the longer-term, large strain readjustment of the clay structure (Graham, 1974). This behaviour is most easily observed in oedometer tests where it is manifested as the characteristic preconsolidation pressure (p_c') break in the semi-logarithmic plot of voids ratio versus effective vertical pressure. In undrained triaxial compression tests it is represented by the maximum deviator stress. The concept of the limit-state surface in a clay is simply a generalization of the overconsolidation effect commonly observed in oedometer tests.

Most natural clays appear to have developed an over-competent grain structure (Bjerrum, 1967; Graham, 1974; Crooks and Graham, 1976) which can withstand stresses somewhat higher than their in-situ stress levels without an appreciable breakdown or 'yield' of their grain structure. The causes for this over-competency are many (Graham, 1974).

For example, overconsolidation due to desiccation, groundwater level changes and erosional off-loading cause the clay structure to adjust to stress levels higher than its present in-situ stresses. This leaves the clay with a reserve resistance, above the structural strength it would have at the in-situ stress level if it remained normally consolidated. Bjerrum (1967) showed that an over-competent structure has developed in Norwegian clays by a combination of the following: depositional environment and subsequent geochemical changes; and delayed compression or aging. In addition, cementation has been shown to cause an over-competent structure in some Canadian clays (Sangrey, 1972).

The detailed determination of the yield envelope of a natural clay is difficult because of the natural variability of clay deposits. In order to avoid these difficulties, it is advisable to carry out the entire test program on large samples originating from the same depth[*]. The use of block sampling techniques is practically mandatory to ensure that all samples have been submitted to the same geological processes and stress history (Leroueil and Tavenas, 1977). Bjerrum and Kenney (1967) showed that the stress-strain behaviour and the strength of sensitive clays are intimately related to the grain structure; that is, to the physical arrangement of soil particles. Eden (1971) demonstrated the reductions in both strengths and preconsolidation pressure caused by various tube samplers in stiff clay from Ottawa. La Rochelle and

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[*] Graham (1974), Mesri (1975) and Crooks and Graham (1976), have drawn attention to the usefulness of preconsolidation pressure p_c' in "normalizing" the behaviour of samples from different depths.

Lefēbvre (1971) established the influence of tube sampling on the 'strength part' of the yield envelope of the St. Louis clay. More generally, sampling disturbance can induce significant changes in the shape and position of the yield envelope of natural clays by affecting the clay structure.

Tavenas and Leroueil (1977) confirmed that the magnitude of the preconsolidation pressure governs the position of the yield envelope in stress space (Fig. 2.1). Based on their experimental investigation, they further concluded that all the factors which affect the preconsolidation pressure would also affect the entire limit-state envelope. It was in this connection that the work of Bjerrum on the effects of aging and strain rates on preconsolidation pressure was introduced to studies of yield envelopes. Bjerrum (1967) showed that the aging of clays under constant effective stresses causes a reduction in voids ratio due to secondary deformations, and that this reduction in voids ratio results in an increase in the apparent preconsolidation pressure. Tavenas and Leroueil (1977) showed that the aging of a clay results in a homothetic displacement of the entire yield envelope in stress space towards higher pressures and strengths.

Crawford (1964) and Bjerrum (1967) both demonstrated that the apparent preconsolidation pressure of a clay is reduced if the rate of loading is reduced, or if the duration of loading is increased in oedometer tests. Bjerrum showed that this effect was actually another materialization of the secondary consolidation phenomenon caused by aging. With respect to the effects of strain rate, Tavenas and Leroueil (1977) using oedometer tests and triaxial tests, confirmed the effect of rate, or duration of loading, on the preconsolidation pressure and yield envelope. They showed that the preconsolidation pressure of a clay is reduced if the duration of loading is increased. Similarly, undrained triaxial tests at different strain rates indicate a reduction in strength as strain rate decreases. More importantly, the displacement of the yield envelope indicated a homothetic movement inwards with time. On this basis Tavenas and Leroueil (1977) concluded that the known effects of aging and strain rate on p_c' applied to the entire yield envelope. This hypothesis that the time-dependent behaviour of a clay is completely described by the time-dependent displacement of its limit-state surface is known as the YLIGHT model. It was confirmed in a later paper by Tavenas et al. (1978b). Additional research is required to quantify this time-dependence, particularly for clays other than the Champlain Sea Clays tested by Tavenas and his co-workers.

2.4 YIELD ENVELOPES OF LAKE AGASSIZ CLAY - A REVIEW

The applicability of the limit-state concept is part of a larger investigation by the geotechnical group at the University of Manitoba into the geotechnical properties of the glacial Lake Agassiz clay which underlies the Winnipeg area. Preliminary information was presented by Baracos et al. (1980) and Noonan (1980). Yield envelopes were found from intact overconsolidated clay samples taken from various depths. A summary of the existing information is presented in Fig. 2.2. As proposed by the YLIGHT model, the yield envelopes at different depths were found to be homothetic. However, the trimming and testing techniques in these earlier tests were difficult due to the highly