THE UNIVERSITY OF ALBERTA

A LITERATURE REVIEW OF STABILITY OF SLOPES IN CHAMPLAIN CLAY

by

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A REPORT

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Dr. N. R. Morgenstern,
Department of Civil Engineering,
University of Alberta,
Edmonton, Alberta,
Canada.

Dear Sir:

It gives me pleasure to submit this report on the stability of slopes in Champlain clay. The report has been prepared in fulfillment of the requirements of the Department of Civil Engineering for the course Civil Engineering 600.

I trust it meets with your satisfaction.

Yours truly,

Marc Chatillon

Marc Chatillon.

ABSTRACT

The objective of this report was to review available literature on the subject, "Slopes in Champlain Clay".

The geological events leading to the formation of the Champlain sea are discussed. With the help of 16 case histories regional properties of the Champlain clay are shown.

Recent developments in the analysis of slope stability are discussed. The dilative and post peak failure envelopes are compared. Further geotechnical problems when dealing with the Champlain sea sediments are exposed.

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CHAPTER I

INTRODUCTION

Over the years, there have been many disastrous slides in eastern Canada's lowlands where a material known as the "Champlain clay" is present. Chagnon (1968) reported 686 scars in a recent air photo investigation of the lowlands in the province of Quebec. In this investigation only scars that were undisputably attributed to a slide movement were counted. If we consider the ones that have also occurred in Ontario, the total is well over 700. Records describe slides going back as far as 1840. Published information of these earth movements indicates a loss of close to 100 lives and approaching 10,000 acres (Eden 1973).

There are many names for the clay found in eastern Canada's lowlands. They are often referred to as Leda clays. This name was given to them by Sir William Dawson when he identified the most common fossil found in it as "Leda glacialis". More recent work has disproved this theory and the clay is more properly called Champlain clay (Eden and Crawford 1957; Gadd 1960; LaRochelle et al. 1970). The name Leda had wide acceptance but is slowly losing ground to the more correct name, Champlain clay. They also have been called Laurentian or Rideau clays (Eden and Crawford 1957).

Whatever the name, there are many papers which have tried to pierce the many special problems encountered when dealing with the Champlain sea deposits. This paper treats one of these problems: slope stability - with a greater emphasis on long-term slope stability.

We shall first look at the geological events leading to the deposition of these sediments in order to establish regional characteristics. This will lead us to the third chapter where the properties of the clay will be described. Regional characteristics will be more clearly defined in this chapter with the help of some 16 case histories. The next step, chapter four, will explore the various views now being presented in the literature to establish a basis for evaluating long-term slope stability problems. In the fifth chapter, we shall look at various other problems that so far have not been solved and have a direct bearing on the problem at hand, slope stability.

Slope failure in Champlain clay may take various forms. It may be a single slide, a retrogressive slide, or a flow slide. Whatever the final outcome the initial trigger is always a small circular slip which progresses from that point on (Bjerrum et al. 1969).

The disastrous slides are of course the retrogressive slides and the flow slides. The first is characterized by a series of closely spaced circular slips leaving a jagged topography in the bowl. The material between the slips is relatively undistrubed. However, there is some completely remolded material forming a small apron at the toe of the slide. A recent example of this type of slide is the one that occurred on the South Nation River in May of 1971. At the other end of the scale, there are flow slides where the material turns to a viscous liquid and flows out of the crater. An example is the Toulnustouc slide that occurred in May of 1962. There are of course the in-between slides, the retrogressive flow slides also called earthflows. They are characteristic of most slides and are especially noticeable by their pear shaped craters (Figure 1.1). The slide that occurred at Breckenridge in 1963 is an example.

These different modes of failure are controlled by the properties of the clay and often by the geology of the area.

CHAPTER II

GEOLOGY

2.1 Introduction

In this chapter the geological history of the eastern lowlands will be studied. This area includes, the St. Lawrence lowlands, the Outaouais valley and the lac St. Jean region. This was the extent of the Champlain sea. Figure 2.1 shows the geographical distribution of the sensitive clays which were deposited during the life of this sea.

2.2 Prior to the Champlain Sea

The activities prior to the Champlain sea vary with the regions. In the Outaouais area, evidence of only one southward moving glaciation was found. Hence, in this area we have a till directly above bedrock above which will be deposited the marine clays. Glacial lake varves are sometimes present directly above the till in the Outaouais area but not as a mappable unit. These indicate the presence of a long narrow glacial lake along the Rideau valley that existed for only a short time before the invasion of the Champlain sea (Gadd 1962).

In the central St. Lawrence region, the stratigraphy is much more complicated. There is evidence of two glacial advances, between which there was a non-glacial period, the St. Pierre interval. The first glacial advance occurred prior to 4,000 years B.P. (before present). This southward advance blocked off the northerly drainage and formed a glacial lake in which were deposited varved sediments. The advance of the glaciation terminated this glacial lake and overrode these varved sediments. This period was followed by the St. Pierre interval which is evident today by the presence of highly compressed peat layers in the stratigraphy. This phase was followed by another glacial advance which again formed a glacial lake (Deschaillon) in this region. Again varved clay sediments were deposited. These were overridden by the advancing glaciation which deposited a sandy grey till (Gentilly till) (Gadd 1971).

2.3 Formation of the Champlain sea.

As the ice started to retreat in a north, north-easterly direction, another glacial lake was formed. However, somehow, the ice blocking the natural northerly drainage to the sea retreated promptly, allowing saline water to invade these isostatically depressed areas. This was the formation of the Champlain sea.(Kenney 1964). This sea can be separated into three basic regions: the central St. Lawrence lowlands, tha Outaouais valley, and the Saguenay region. The Champlain sea did not invade these areas all at once. Each region has its own special properties which differentiates it from the others. These will be explored in the next chapter.

2.3.1 The Central St. Lawrence Lowlands

? Sea before the glaciation page 6

This was the first region to be invaded. The earliest possible date of the Champlain sea is about 11,800 years B.P. (Kenney 1964; Elson 1969). Geologically there is nothing peculiar to this region. Fine grained sediments were deposited in a saline to brackish water environment. The Champlain sea ended due to isostatic uplift. This is estimated to have occurred some 9500 years ago.

2.3.2 The Outaouais Valley

It was established that the earliest possible date for the existence of the Champlain sea in the Outaouais valley is approximately 10,800 years B.P. During the time the sea was at its maximum, only the land now above 650 feet remained dry. However, marine or estuarine clays are only found at elevations below 375 feet. When the surface elevation is lower than about 325 feet the predominant surface sediments are non-marine, indicating a local change of the salinity of the water when the sea level was at or near 325 feet in Ottawa (Gadd 1962).

It is reasoned that the salinity of the water changed rapidly from a brackish to a fresh water environment, suggesting a possible redeposition of the upper sediments in this region (Gadd 1962; Sangrey and Paul 1971). The question then is posed, how do these upper clays form a flocculated structure when deposited in fresh water? It has been suggested that the open structure can be attributed to residual cations from the original deposits (Crawford 1965, 1968). Kenney (1964) suggested that a fresh water environment existed after 10,500 B.P.

There are two explanations put forward for this sudden abundance of fresh water. The second one is presently preferred (Gadd 1962; Kenney 1964).

1. The land rebounded from its depressed position, leaving a shallow sea. Fresh water, being in great abundance from retreating glaciers, prevented the entrance of salt water.

2. A great volume of fresh water was introduced from a fresh water lake now known as lake Huron.

In any event, it has been proposed by Sangrey and Paul (1971) that this particular geological event was of great importance with respect to slope stability problems.

2.3.3 <u>The Lac St. Jean Region</u>

Karrow (1972) differentiates between the occurrence of the Champlain sea and the Laflamme sea. He estimates that this marine environment existed from 9500 years B.P. to 8500 years B.P. However, most authors that have worked in this area have included this geological event as part of the Champlain sea (LaRochelle et al. 1970; Tavenas et al.

1971). The properties of the clay are slightly different from the previous two regions, though the same type of disastrous slides occur. This is probably the reason why geotechnical engineers do not differentiate between these geological events.

2.4 End of the Champlain sea

As stated previously, during the last glacial advance of the Wisconsin age, the northern part of North America was depressed several hundred feet. The Champlain sea was formed when the glaciers retreated and saline water invaded the depressed land. It took over 4,000 years for isostatic uplift to bring an end to the Champlain sea by raising the land above existing sea level (Gadd 1956; Karrow 1961; Crawford 1968). It was estimated by Kenney (1964) that Nicolet (Quebec) has risen 750 feet and Ottawa (Ontario) has risen 800 feet since post glacial marine inundation occurred.

2.5 Conclusion

Several factors can be learned about the sediments of the Champlain sea if one looks at the geology of the regions as previously discussed.

First, the waters were probably marine everywhere but the salinity was certainly variable. We would expect the salinity to increase with depth of sediment (Elson 1969) and with proximity to Quebec city (Wagner 1970).

Secondly, we can expect in the Outaouais area, two types of clay (Gadd 1962).

1. The older clay which was deposited in a marine or brackish water environment.

2. The younger clay which was deposited in a fresh water or lacustrine environment but still retains a flocculated structure.

Thirdly, if one looks at the properties of the clay in various parts of the Champlain sea, a noticeable trend can be observed. With increasing distance inland from the ocean, the clay fraction, plasticity and natural water content increase. Liquidity index and sensitivity vary between wide limits in specific locations (Crawford 1961 a). There are other similarities but these will be discussed further in the next chapter which deals with the properties of the clay.

A fourth point of interest is the thickness of the marine deposit. It varies greatly, mainly because it conforms to the lower surface. Generally speaking in the Cornwall-Cardinal area the marine clay is 35 to 80 feet deep; in the Outaouais area the maximum depth varies from 100 to 200 feet; on Montreal island the maximum depth varies from 80 to 145 feet; in the Becancour area many of the deposits are more than 100 feet thick (Karrow 1961).

Isotatic uplift has elevated the land above its former depressed position. Hence, most streams are youthful and erosion aided by weathering and dessication is very active.

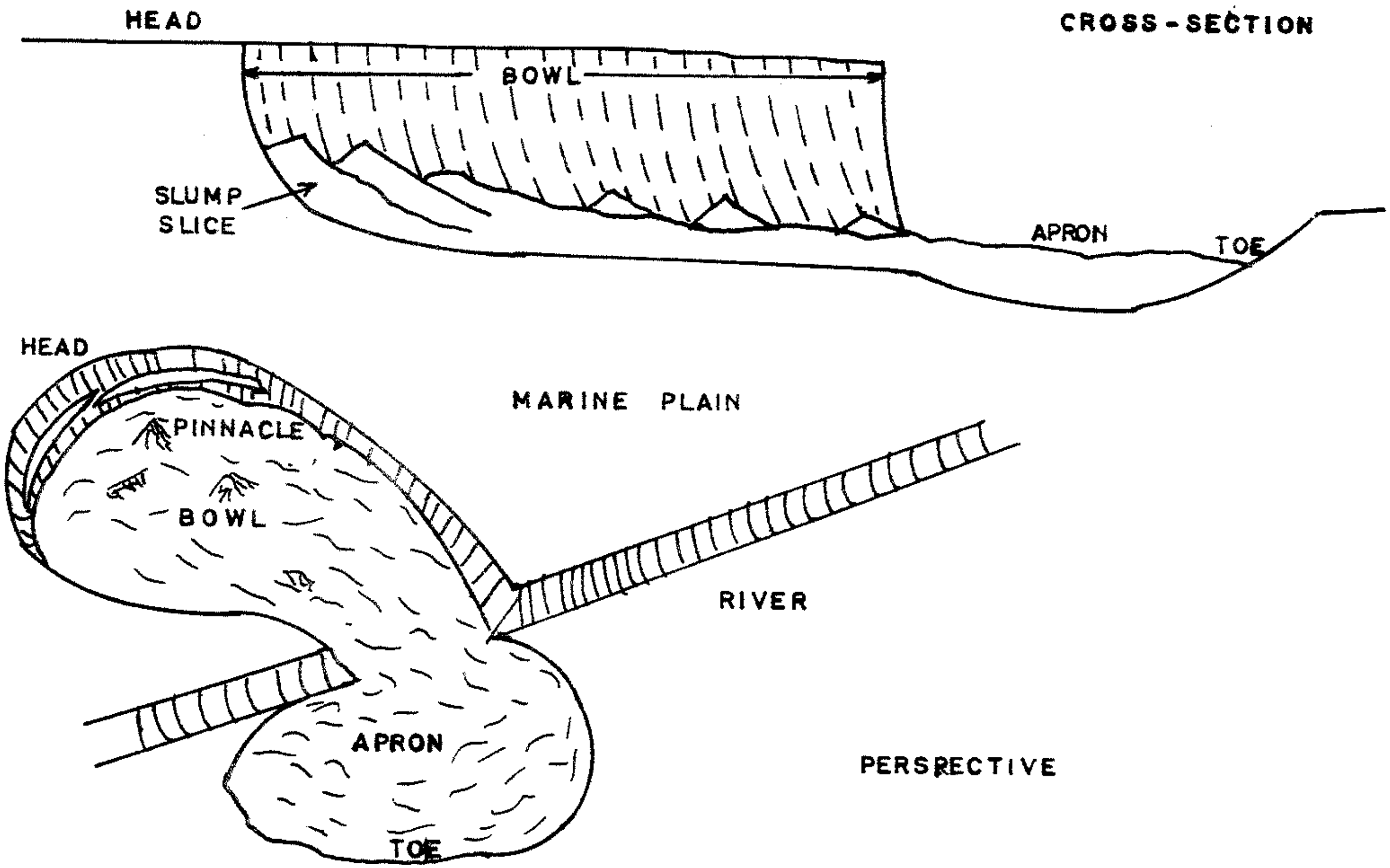

FIGURE 1.1 TYPICAL EARTHFLOW (KARROW 1972)

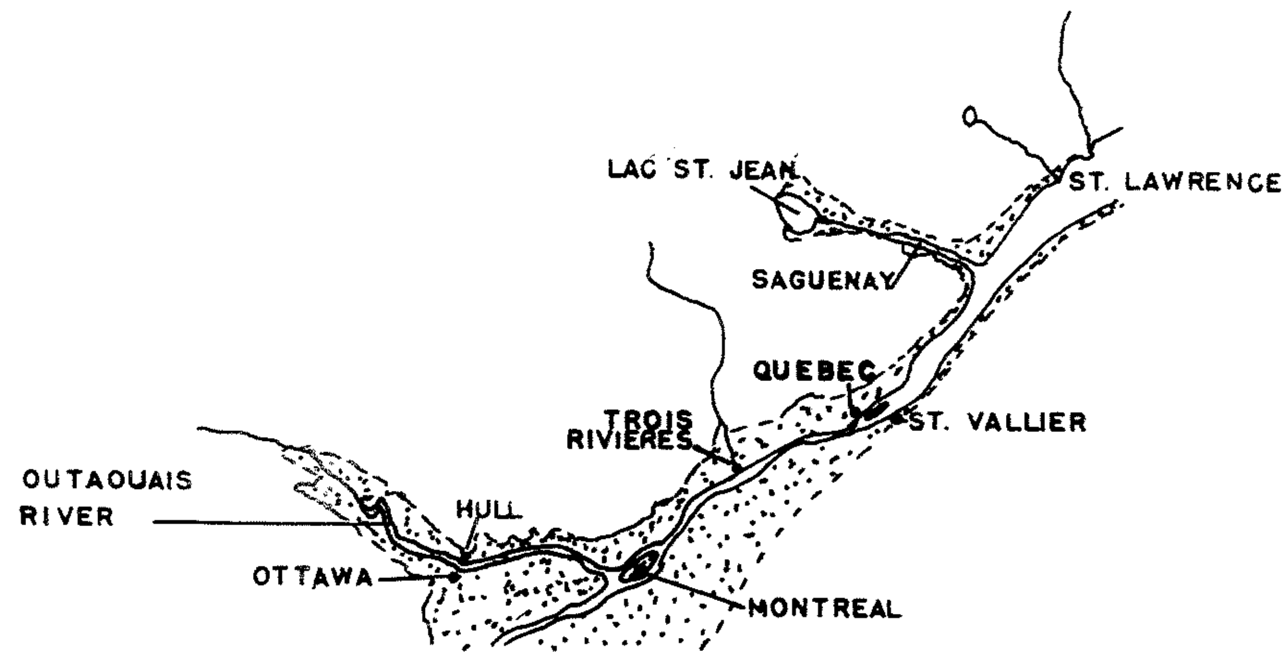

FIGURE 2.1 GEOGRAPHICAL DISTRIBUTION OF CHAMPLAIN SEA SEDIMENTS

CHAPTER III

HISTORY OF LANDSLIDES AND PROPERTIES OF THE CHAMPLAIN CLAY

3.1 Introduction

As defined previously there are three basic regions of the Champlain sea: The Saguenay River and the lower St. Lawrence valley, the central St. Lawrence lowlands, and the Outaouais River valley. We shall attempt in this chapter, with the help of documented landslips to gain a better understanding of the properties of the clay in the regions previously defined.

3.2 Previous Landslips and General Characteristics

The history of landslips in these areas stretches back to the first years of recorded history in this country. Nowadays with the help of air-photos and various dating techniques, more ancient massive landslips have been observed. Some work of this kind has been done by various authors (Chagnon 1968; LaRochelle et al. 1970).

Table 3.1 gives a chronological list of documented earth movements in Champlain clay. This is an incomplete list but contains the better documented slips that have occurred. Some older slides are not listed in Table 3.1. for example Notre-Dame-de-la-Salette, 1908, which took 33 lives. They are important in a historic sense, and are described as such in the literature. In this study, they are of no quantitative use.

If we analyze this table we may note that 10 of the 16 slides are reported to have occurred when water conditions were at a maximum. Hence, we can deduce that springtime or heavy rains after a very hot summer are conditions conducive to landslides in the Champlain clays. Of the 16, 8 occurred in the springtime and 5 in late summer or autumn. Of the 3 that are left, one is ancient (it is not known exactly when it failed); one occurred in the summer and the other in the winter. It seems clear at this point that water conditions in a slope in Champlain clay are critical to its stability.

Table 3.2 (a) and 3.2 (b) give a list of the engineering properties of the clay at each site previously described. Some averaging had to be done. Most of the data for this table has been taken directly from the corresponding referenced author. Data has also been taken from Mitchell and Markwell (1974) who have extended some studies. They have gathered information on 41 slides that have occurred in the sediments of the Champlain sea and Lake Ojibway-Barlow. This paper only deals with the Champlain clay and it is believed that the slides described in Tables 3.1 and 3.2 are representative of the areas so that some generalization may be recognized.

We note immediately that no failure has occurred on natural slopes that have an inclination less than approximately 25°. One has occurred at an inclination of 20° in Hawkesbury, 1955, but this was a cut slope.

The next point to notice is that the natural water content is close to or greater than the liquid limit. This is a characteristic of a quick or sensitive clay. That is the liquidity index is close to or greater than unity.

The sensitivity measurements vary greatly but they are undoubtedly indicative of a sensitive soil. It varies from 2 to infinity over the whole Champlain sea and often over an order of magnitude within the same area. We shall see in chapter V that the numbers obtained are very much dependent on the method of evaluation used (Eden and Kubota 1961).

The other properties such as salt content, clay size, undrained shear strength, all vary greatly but we shall try to analyze them to account for any trend that might exist.

3.3 Saguenay and Lower St. Lawrence Region

First let us look at the Saguenay and lower St. Lawrence region. There are reports that the clays in this area are either heavily consolidated or very strongly bonded (Eden and Mitchell 1973). Two of the three case histories that we have in Table 3.2 (b) demonstrate this clearly

(9,16).[1] Their shear strength can be measured up to 3.5 - 4.0 tons per square foot. However, the data recorded from the Rimouski slide (6) shows that this area has a low strength. Other characteristics lead us to believe that even though this slide is geographically in the lower St. Lawrence area, it should be part of the central St. Lawrence region or a transition zone.

We can also note that the clays in this area are siltier than in the other two areas. This is reflected by the liquid limits which are lower than in the other two regions. Their natural water content is generally higher than the liquid limit. Their sensitivity is also very high. It frequently has a value close to infinity (LaRochelle 1972).

Some of the largest flow slides recorded have occurred in this type of material. Both the examples we have studied here have displaced material in excess of 5 million cubic yards.

3.4 The Central St. Lawrence Lowlands

The material in the central St. Lawrence lowlands is the one we shall look at now. It is reported that the clays in this area tend to be softer and slightly over-consolidated (Eden and Mitchell 1973). The occurrence of these properties will be shown with the help of our case histories in this region (2,4,5,7).

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[1]Refers to numbered case histories Table 3.1, 3.2 (a), 3.2 (b).

The undrained shear strength varies from 0.3 to 0.8 tons per square foot. The clays are then much softer than in the Saguenay region and as we shall see only slightly softer than in the Outaouais region.

Again here the natural water content generally exceeds the liquid limit. However, the liquid limits are approximately 30 percent higher than they were in the Saguenay region. This probably reflects the higher clay size content. However, this property is quite variable in our case histories. It varies from 36 to 80 percent. There is however an indication that the material gets siltier with depth in Nicolet (7). There is unfortunately not enough information to verify this on other sites. We may conclude that the clays in this region are more clayey and softer than in the region previously studied.

In our four examples the liquidity index varies between 1.0 and 1.9 which again shows a sensitive clay. The sensitivity however varies greatly, even within the same slide.

The salt content varies greatly also. There is an indication that it increases with depth. This reflects probably the transition from a marine to a fresh water environment. However, contrary to the Norwegian clays it has been shown that the properties of the Champlain sea clays are independent of salt content (Crawford 1968). In any case, it would be interesting to find out if a reduction in salt content on a site is the result of the leaching process or not. Because if leaching is going on, then there must exist a hydraulic gradient which is quite detrimental to the stability of a slope. LaRochelle (1972) reported a hydraulic gradient of 0.9 at the St. Louis slide (5). This high value certainly played a great part in causing the instability of this slope. This factor shows clearly the poor drainage conditions that exist throughout the central St. Lawrence lowlands (Eden and Mitchell 1973).

3.5 The Outaouais Valley

The third and last region of the Champlain sea is the Outaouais valley. It is probably the most studied of the three regions. Nine of the sixteen case histories are situated in this region (1,3,8,10,11,12,13,14,15). This region can be differentiated from the others by its thick weathered crust, extending to depths of 10 to 20 feet (Eden and Mitchell 1973). This weathered crust exists in the other two regions but it is usually thicker and better defined in the Outaouais area.

We notice here that the natural water content ranges usually within plus or minus 10 percent from the liquid limit. The liquidity index is close to and is often smaller than unity. This is an indication that the material in this region is not as sensitive. Usually the flow slides are of a smaller nature than in the other two regions.

However there are always some exceptions to the rule. The South Nation river landslide (15) is the largest landslide that has occurred in this region in recent history. It is second in extent to the St. Jean Vianney landslide. The clay size content of the South Nation river material is comparable to the St. Jean Vianney material. It is quite silty. It is not representative of the rest of the material in the Outaouais valley which on the average is a little more clayey than the material in the central St. Lawrence region.

The salt content is again subject to controversy. However, it is generally accepted that there has been a reworking or redeposition of the upper sediments in a fresh water environment in some areas of the Outaouais valley (Sangrey and Paul 1971).

The undrained shear strength is however variable and usually increases with depth below the weathered crust. It varies from soft to stiff. It is generally a little stiffer than in the central St. Lawrence region. It also has been related to the preconsolidation pressure (Eden and Crawford 1957). The crust itself is usually very stiff and decreases rapidly in strength to the unweathered material.

3.6 Conclusion

We have seen in this chapter that the three basic regions of the Champlain sea do have some distinct differences.

These may help us understand the processes of landslides in the Champlain sea sediments.

The one property that has not been mentioned so far is the stress-strain property of these clays. They are directly involved with the landslide analysis and will be treated in the next chapter.

TABLE 3.1

SLIDES IN CHAMPLAIN CLAY

Number	Name	Date	River	Acres	Cubic Yards $X10^6$	Victims	Weather Conditions	Reference
1	Green Creek	Ancient	Outaouais	30	2	-		Crawford & Eden 1962
2	St. Thurbide	7 May 1898	Blanche	86	3.5	1	Great amount of snow	Dawson 1899
3	Poupore	11 Oct 1903	Lievre	100		-		Ells 1903
4	St. Vallier	24 July 1935	Des Meres	15		-		Beland 1956
5	St. Louis	18 May 1945	Yamaska	7		-		Beland 1956
6	Rimouski	3-6 Aug 1951	Rimouski	25	1	-		Meyerhoff 1954
7	Nicolet	12 Nov 1955	Nicolet	6	0.25	3	Dry summer Rainy autumn	Hurtibise & Rochette 1956
8	Hawkesbury	7 Dec 1955	-	12	0.5	-	Dry summer Rainy autumn	Eden 1956

TABLE 3.1 (Continued)

Number	Name	Date	River	Acres	Cubic Yards $X10^6$	Victims	Weather Conditions	Reference
9	Toulnustouc	23 May 1962	Toulnustouc		5	-	Heavy spring Rain	Conlon 1966
10	Breckenridge	20 Apr 1963	Breckenridge	1	0.03	-	Heavy Rain	Crawford & Eden 1967 Mitchell 1970
11	Orleans	Oct 1965	-		0.002	-	Heavy Rain	Eden & Jarret 1970
12	Rockcliffe	Apr 1967	Outaouais		0.03	-	Snowmelt and Heavy Rain	Eden & Mitchell 1970 Mitchell 1970
13	Pineview	Nov 1967	-		0.002	-		Mitchell 1970
14	Rockcliffe	Spring 1969	Outaouais			-	Snowmelt	Sangrey & Paul 1971
15	South Nation	May 1971	South Nation	70	8	-	Large snow Slow melt	Eden et al.1971
16	St. Jean Vianney	4 May 1971	Petit Bras	70	9	31	Rain after Snowmelt	Tavenas et al. 1971

TABLE 3.2 (a)

PROPERTIES OF SOILS IN CHAMPLAIN CLAY

Number	Upper Terrace Elev (Ft)	Height of Slope (Ft)	Avge Inclin at Scarp	Nat. Water Count (%)	Liquid Limit (%)	Plastic Limit (%)	LI	Sensitivity	Region
1				72	70	30	1.1	25	III
2	175	30		44	33	21	1.9	$\leqslant\infty$	II
3				45	61	38	0.3	3-21	III
4				60	60	23	1.0	7-20	II
5				65	50	25	1.6	12-50	II
6				30	40	20	0.5	2	I
7	70	30	$\simeq 30°$	65	55	23	1.3	9	II
8	225	47	20°	80	64	26	1.4	27	III
9	275	100	30°	32	20	16	3.5	high	I
10	92	90	$\simeq 25°$	76	63	28	1.4	12-150	III
11	238	30	35°	65	70	30	1.0	35	III
12	180	40	24°	65	70	30	0.9	181	III
13	210	50	28°	60	70	30	0.8		III
14	178	40	25°						III
15	230	80	25°	70	70	30	1.0	10-100	III
16	200			39	32	18	0.9	$\leqslant\infty$	I

I = Saguenay and Lower St. Lawrence II = Central St. Lawrence III = Outaouais Valley

TABLE 3.2 (b)

PROPERTIES OF SOILS IN CHAMPLAIN CLAY

Number	Clay Size Cont (%)	Salt Content	C_u Ton/ft^2	c' kg/cm^2	ϕ'	r_u	R = Region
1	75		0.4-1.2			0.62	III
2	36		0.8				II
3	65		0.3-1.2				III
4	65	4	0.35				II
5	80	0.4				0.9	II
6	high		0.25-0.5				I
7	73 up 50 below	0.5 up 9.0 low	0.3 up 0.6 low				
8	74	0.3	0.4				II
9	30		≤4				III
10	82		0.4-0.8	0.5	35°	0.5-0.62	I
11		<1.0	0.5	.106	34.4°	0.59	III
12	54		0.3-1.0	.12	33°	0.6	III
13	60		0.6-1.2				III
14				.002	36.8°	0.62	III
15	45-57		0.5				III
16	27-46		≤3.5				III
							I

I = Saguenay and Lower St. Lawrence   II = Central St. Lawrence   III = Outaouais Valley

CHAPTER IV

LANDSLIDE ANALYSIS

4.1 Introduction

There are two basic concepts that have emerged from about 10 years of active research into the mechanisms of slope failure in the Champlain clay. The first is the so called dilation/frictional approach and the second the so called progressive failure approach.

A major step forward was accomplished when Kenney and Ali (1966) in a discussion of a paper by Crawford and Eden (1966) pointed out that the initial slide is only very small compared to the mass that retrogresses after this initial drained failure. They also noted that this bonded Champlain clay suffered important decreases in strength at small confining stresses. The question that they posed at the time was, does this clay fail as an intact material or rather as a material with inherent defects?

At about the same time, Conlon (1966) initiated the idea of progressive failure with his study of the Toulnustouc landslide. The very brittle character of the clays suggested to him that the failure took place because of a local failure which in turn overstressed the material up slope therefore failure occurred in a progressive manner. He also realized the importance of the level of consolidation pressure in a triaxial test.

In the following discussion an attempt will be made to review the research that has been performed in recent years. We shall be dealing with the "long-term" stability of slopes in Champlain clay. Hence, we are referring to equilibrium ground water conditions and dealing with the effective stress parameters of the soil. For the sake of clarity only the drained triaxial results will be discussed. It is believed that the initial slide fails in a drained manner and that subsequent retrogression should be analyzed using a smaller pore pressure parameter than the one used in the initial slip. Ultimately slope failure in a retrogressive slide should be analyzed using a $\phi = 0$ analysis (Mitchell and Markwell 1974). However, because most Champlain clays have a high A value the individual slips immediately after the initial slide should probably be analyzed in an undrained fashion. In our discussion we shall be involved only with the trigger or initial slides. Hence, we shall be looking at the drained behaviour of the Champlain clay.

4.2 Stress-Strain Behaviour and Mohr Envelope

4.2.1 General

It has been recognized that the drained (and also the undrained) strength of the Champlain sea sediments is dependent on the confining or consolidation pressures under which a sample is tested. The Mohr envelope has been divided into three phases. Figure 4.1 typifies the shape of the envelope (Mitchell 1970 (a); Jarret (1972).

Phase I occurs when the consolidation pressure is greater than the bond strength or the preconsolidation pressure. The material fails as an unstructured mass at very large strains (in the order of 30 percent). The stress-strain behaviour is that of an elasto-plastic strain hardening material (Figure 4.2) (Lo 1972).

When the cemented structure controls the failure envelope, the second phase is in evidence (Figure 4.1). The stress-strain curve is of the type shown in Figure 4.2. Failure takes place usually at low strains (in the order of 3 percent).

Phase III occurs when failure is induced at low effective confining stresses. It is in this region that most if not all the working stresses of slopes are situated (Jarret 1972). The importance of only using stresses that are applicable to the field problem in the laboratory is quite evident from the previous discussion. This phase is also the one in which there is the most controversy. During the rest of this paper we shall limit our discussion to this important phase.

4.2.2 Low Confining Pressure Stress-Strain Behaviour

Generally the controversy stems from the fact that two types of stress-strain curves have been obtained when attempting to define the failure envelope at low confining pressures.

The first type of failure can be described as an elasto-perfectly plastic behaviour. This is shown in Figure 4.3 (b). This type of stress-strain curve has been obtained from a p test $(\frac{\sigma_1' + \sigma_2' + \sigma_3'}{2} = \text{constant})$ in several case histories from the Outaouais valley (Mitchell 1970 (a)).

The second type of failure is one characteristic of very brittle material. It was however obtained from an ordinary strain controlled consolidated drained triaxial test. Figure 4.3 (a) shows a typical stress-strain curve. The peak is usually reached at strains smaller than 1 percent. This curve is typical of the ones obtained for clays in the central St. Lawrence region and Saguenay area.

Before going on to discuss the different failure envelopes we shall attempt to explain these differences and establish a mode of failure.

The first difference between the curves is of course the testing method. One is obtained from a p test, the other from an ordinary strain controlled test. Mitchell (1974) in his arguments favouring the use of the p test, discredits the standard triaxial by showing that the normal stress $(\frac{\sigma_1' + \sigma_3'}{2})$ at failure is well outside the range of mean average stress considered operative in a slope. He further argues that such stress would hamper the dilative failure of the samples. This fact is substantiated by a standard triaxial test run at very low confining stress by Lefebvre and LaRochelle (1971) which failed in a dilative manner. Other samples in that series tested at higher confining pressures failed in a compressive fashion.

The second inconsistency is that the clays in the St. Lawrence region peak while the tests performed on samples of the Outaouais area do not. The answer to that problem is probably in the nature of the clay itself. The clay in the Outaouais area is a higher, older clay than in the St. Lawrence region. It has been reported (Mitchell 1970) that it is microfissured and has at failure a nodular consistency. It is then presumed that the clays in the St. Lawrence region are not microfissured and the cemented bond must be broken before failure can occur. It is this process that creates a peak. It is then postulated that the failure mechanism is the same and that the nodular structure is present in the St. Lawrence clays but only on the failure plane. A possible analogy to this is reported by LaRochelle and Lefebvre (1970). They have shown that clays from the St. Lawrence region are greatly affected by sampling methods. More precisely they have demonstrated that sampling strains these clays which in turn dampens considerably the peak of a stress-strain curve (see Figure 4.4). It is therefore postulated that the clays in the Outaouais area have been strained on stress relieved thereby creating microfissures while the St. Lawrence clays have not been submitted to such processes.

What then is the failure mechanism of these clays? The recognition of the microfissured nature of the Outaouais clays has played an important part in understanding the failure in Champlain clays. It is believed that as the material tested in the laboratory dilates near failure, negative pore pressures are induced on the failure plane. This increases the effective mean stress $(\frac{\sigma'_1 + \sigma'_3}{2})$ which brings the material to failure. It is postulated that if p tests were run on St. Lawrence clays they would fail in the same manner, in a dilative fashion (as previously discussed).

However, long term tests (3 months) performed by Lo (1972) on St. Lawrence clay suggest that not only peak strength is time rate dependent but that post-peak strength is also affected. He estimates the loss at 10 percent per logcycle of time. This behaviour strongly suggests a progressive failure mechanism leading to failure. However, as discussed previously, it is believed that the standard triaxial test does not represent the failure path of such clays and that its confinement might hamper the dilative failure mechanism. Therefore, long term p tests should be performed to establish if such a time rate dependence does exist.

4.2.3 Low Confining Pressure Failure Envelope

As shown by Figure 4.5 there are three possible failure envelopes to choose from: the peak failure envelope, the post-peak failure envelope and the dilative failure envelope.

Mitchell (1974) argues that the peak strength envelope is a total stress failure and postulates that at very slow strain rates the negative pore pressures set up during the test should tend to equalize. This envelope is then not applicable to slope stability analysis. Lefebvre and LaRochelle (1974) have substantiated this conclusion by trying to analyze two slope failures and obtaining factors of safety which are much too high.

Mitchell (1974) also argues that the post-peak failure envelope is not applicable to slope analyses because it does not represent the true mode of failure. Because of the higher confining pressures, the material is prevented from dilating thereby reducing the failure envelope. Slope stability analyses using this failure envelope would then be estimated conservatively.

It is then postulated that the only acceptable failure envelope is the one obtained from a p test where the confining stresses are consistent with field stresses and a dilative failure is present.

4.3 Analysis of Failure

It is quite evident that the peak failure envelope cannot be used to estimate the stability of a slope. However, the post peak failure envelope has been used by Lefebvre and LaRochelle (1974) to evaluate slope failures at St. Vallier and St. Louis. Their analysis fits well with the actual slop circle at a factor of safety of unity. They attribute the failure to a process of progressive failure. The material tested in a standard triaxial test exhibited a brittle behaviour necessary for the progressive failure concept. Mitchell (1970 (a)) has also had good success with the dilative failure envelope. Failures in the Outaouais area are dilative-frictional in nature. This type of failure is attributed to closely spaced imperfections in the material.

Are there two modes of failure, or can failure be explained by one mode of failure as previously discussed? A key to this problem might reside in the analysis of the Pineview golf club landslide (Mitchell 1970). It is believed that this clay is not fissured (as the ones in the St. Lawrence region). Hence, we can observe that a dilative envelope is obtained at low confining pressures. No complete stability analysis was performed because of the lack of information on the groundwater regime. However, a good correlation between the dilative failure analysis and actual failure mechanism seemed to be obtained.

The importance of knowing the groundwater conditions cannot be emphasized enough. It is believed that groundwater movement is the prime instigator of slope failures. Complete failure of a slope is dependent on the availability of surface water entering via tension cracks to satisfy the dilatant tendency and reduce the effective normal stresses (Eden and Mitchell 1970). So far most landslide investigations have been performed with poor groundwater information. Accurate information about this important parameter is essential in future case histories if any progress is to be made in this field.

Theoretically Mitchell (1974) has presented plausible arguments in favor of the dilative failure envelope using p tests. However, the use of the post-peak failure envelope has also demonstrated good potential in analysis of slope failures (Lefebvre and LaRochelle 1974; Lo and Lee 1974). Lo (1972) admits that the use of the post-peak failure envelope is conservative. The question now remains, how conservative is it? Only a direct comparison of both failure envelopes on a slope failure where groundwater conditions are known at the moment of failure will clarify this question.

4.4 Other Considerations

Important properties of the material have been neglected in our discussion thus far. Such things as anisotropy, rate effects, and end effects, have been intentionally omitted not to confuse the issues any further. However, these characteristics are important and shall be discussed here.

Because of the brittle behaviour of the Champlain sea sediments, Coates and McRostie (1963) report that serious errors are introduced when the ends of samples tested are not parallel.

The influence of rate of testing is a very debated and confused issue. Lo and Morin (1972) report that stress-strain behaviour are dependent on rate of testing. However, Eden and Mitchell (1970) and Mitchell (1970 (b)) report that in the low stress range the stress-strain curves are independent of rate of strain. Rate of strain is an important character that may have far reaching implications in the mode of failure of Champlain clay. More research work should be devoted to this aspect.

Strength anisotropy has been found to be independent of sample orientation by both Lo (1972) and Eden and Mitchell (1970) at low confining pressures. Lo's conclusion is only valid for post-peak or residual strength. He found that peak strength was highly anisotropic.

Sample size for Outaouais clays is an important issue because of the presence of microfissures. Eden and Mitchell (1970) report that an area of 10 square centimeters appears to be large enough to eliminate sample size effects.

There is another important problem, the curvature of the failure envelope either post-peak or dilative. There is a barrier in a triaxial test, at very low confining stresses, where soils cannot be tested. It is the unconfined compression line. By adapting a certain rock testing technique to soil Jarret (1970) provided data to complete the failure envelope. He obtained failure parameters $c' = 0.08$ kg/cm^2 and $\phi' = 45°$. Eden and Mitchell (1970) obtained $c' = 0.12$ kg/cm^2 and $\phi' = 33°$ for the same soil. When used in the stability analysis both sets of strength parameters yielded a factor of safety close to unity. This was explained by the fact that both failure criterias intersected close to the value of average normal stress on the critical circles. However it may be implied that the curvature of the failure envelope is an important aspect of the envelope and that approximating it by a straight line may be introducing substantial error.

4.5 Empirical Approach

Mitchell and Markwell (1974) documented 41 case histories of landslides. They attempted to predict instable areas by the use of an empirical rule based on the study they performed. In every case where large flow slides were sufficiently documented, the value of γH was found to exceed 6Cu, at or near the depth of failure. An area can be considered dangerous if $\gamma H \simeq 6Cu$. Using $\gamma = 2.4\ \gamma'$ they also noted that normally consolidated clays with $Cu/p' \lesssim 0.4$ are susceptible to earthflows.

Even if $\gamma H < 6Cu$ this does not eliminate the danger of sliding. However, chances are that if a slide is to occur, it will be small.

If after such a study it is found that the area investigated could be subjected to failure under the proper conditions, then we may apply the principle proposed by Lo and Lee (1974). They found that a first approximation to slope stability study could be obtained by using the parameters $c' = 0$ and $\phi' = 43°$. Mitchell (1974) presented a table comparing the pore pressure parameter (r_u) for a factor of safety of unity for the dilative failure envelope and Lo and Lee's approximation. We notice that the pore pressure parameter using the dilative approach is either equal to or greater than the pore pressure parameter obtained from an analysis using $c' = 0$ and $\phi' = 43°$.

To estimate how conservative this approximation really is, a few slip circle analyses have been calculated using Bishop's method.

The first one analyzed was the slide that occurred at Rockcliffe (1967) reported by Eden and Mitchell (1970). $C' = 0, \phi' = 43°$ and $r_u = 0.6$ were used on the slip circle C3. A factor of safety of unity was obtained. This again reflects the curvature of the failure envelope as discussed previously.

The second slip circle to be calculated was the circle CA of the Orleans slide reported by Eden and Mitchell (1970).

For $c' = 0$, $\phi' = 43°$ and $r_u = 0.6$ a factor of safety of 0.3 was obtained. For $c' = 0, \phi' = 43°$ and $r_u = 0.4$ a factor of safety of 0.8 was obtained.

Therefore, it is believed that this method of approximation can only be useful if a general idea of the stability of a slope is required. Otherwise, laboratory testing is essential. These analyses also point out again the importance of knowing accurately the groundwater conditions in the slope investigated. Lo and Lee's approximation might in some cases prove to be too conservative.

4.6 Final Remarks

If after preliminary investigation a more detailed analysis is required, at this moment there are two routes to follow.

If the clay is fissured (i.e. Outaouais area) then the dilative failure envelope should be determined with the appropriate p tests at low confining pressures.

If the clay is not fissured (i.e. St. Lawrence) we should determine the post-peak envelope. This failure envelope might be overly conservative. Only further research will determine if the dilative failure criteria is applicable to these intact clays.

It is hoped that one day a generalized failure envelope will be available to determine the stability of slopes in Champlain clay. We could then eliminate the prohibitive costs of determining a failure envelope. Only a few samples could be tested to determine the applicability of the generalized failure envelope to the particular slope.

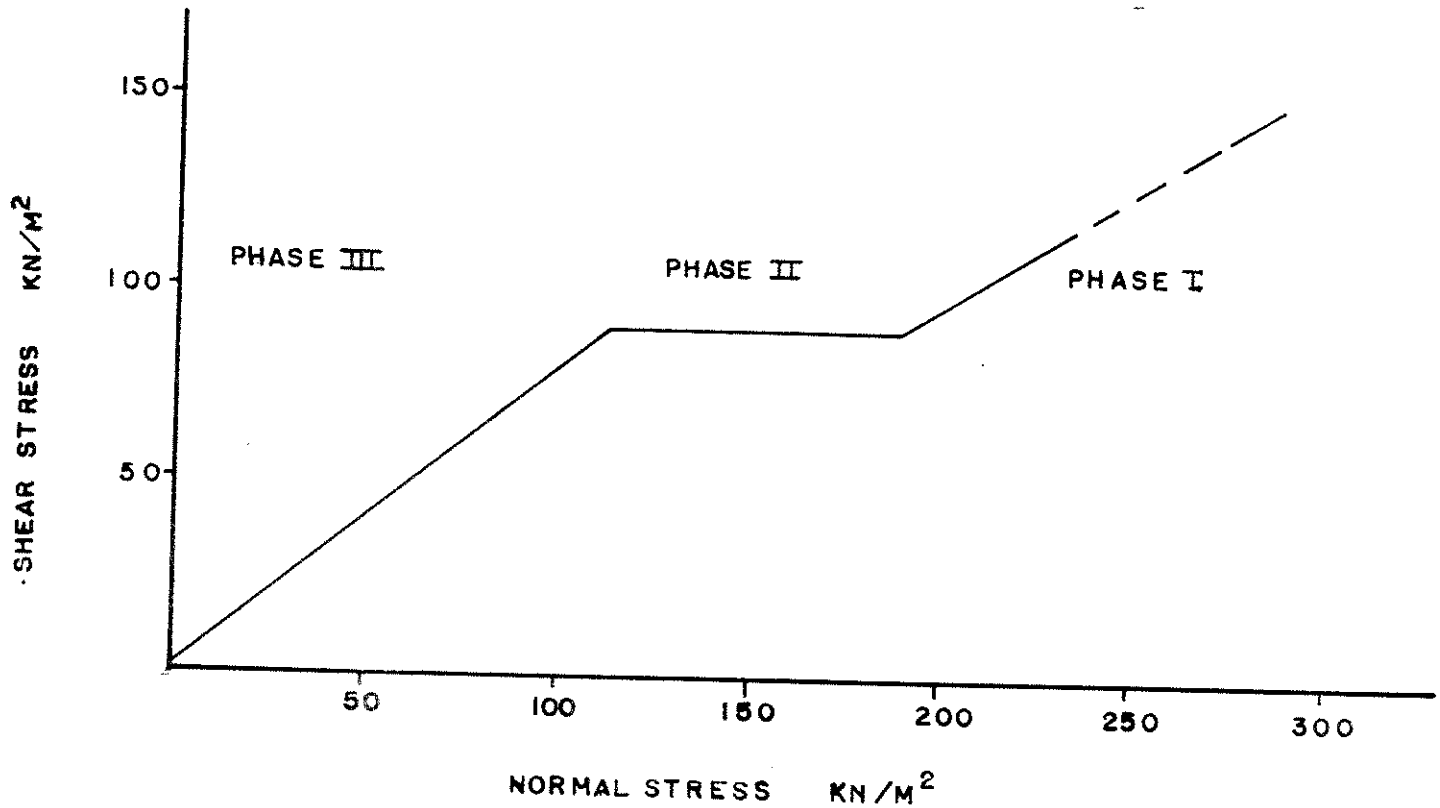

FIGURE 4.1 FAILURE ENVELOPE (OUTAOUAIS REGION) (JARRET 1972)

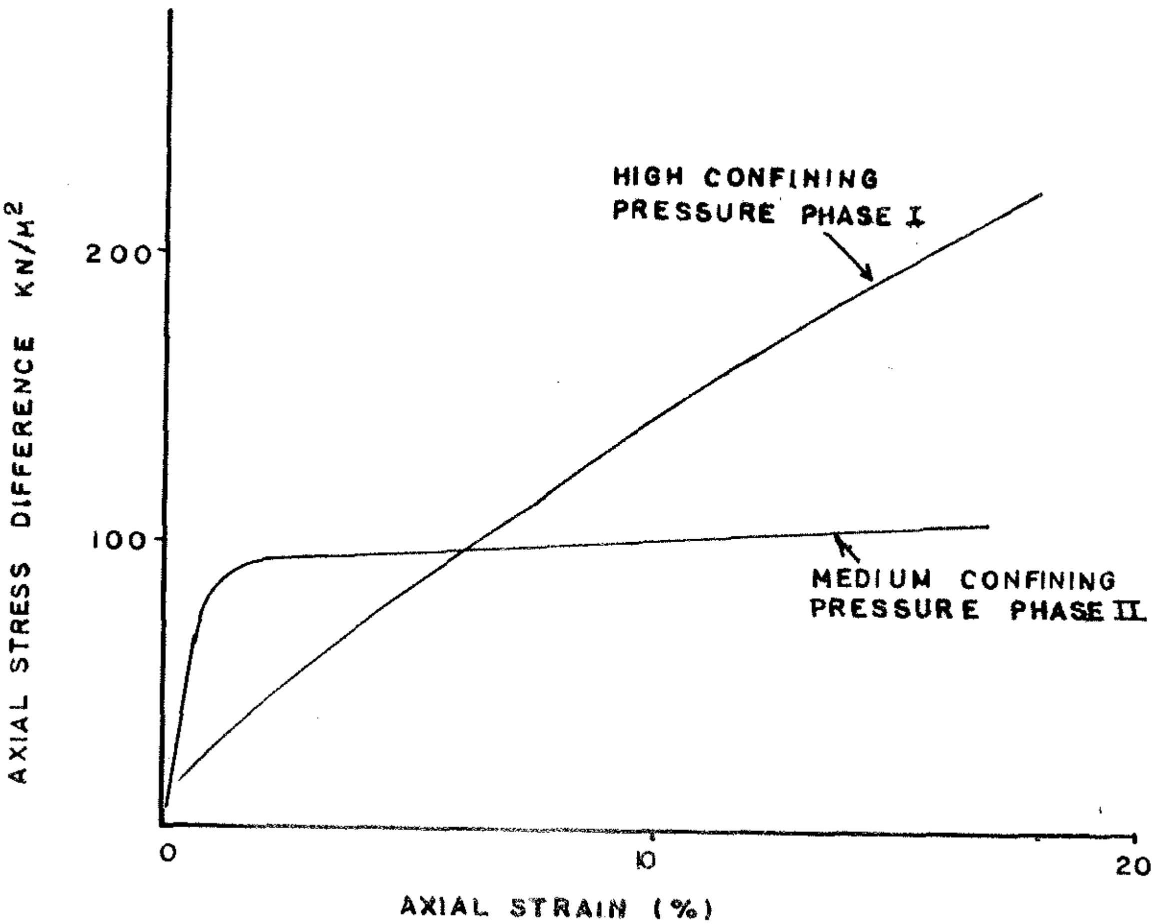

FIGURE 4.2 TYPICAL STRESS-STRAIN CURVE (RAYMOND 1973)

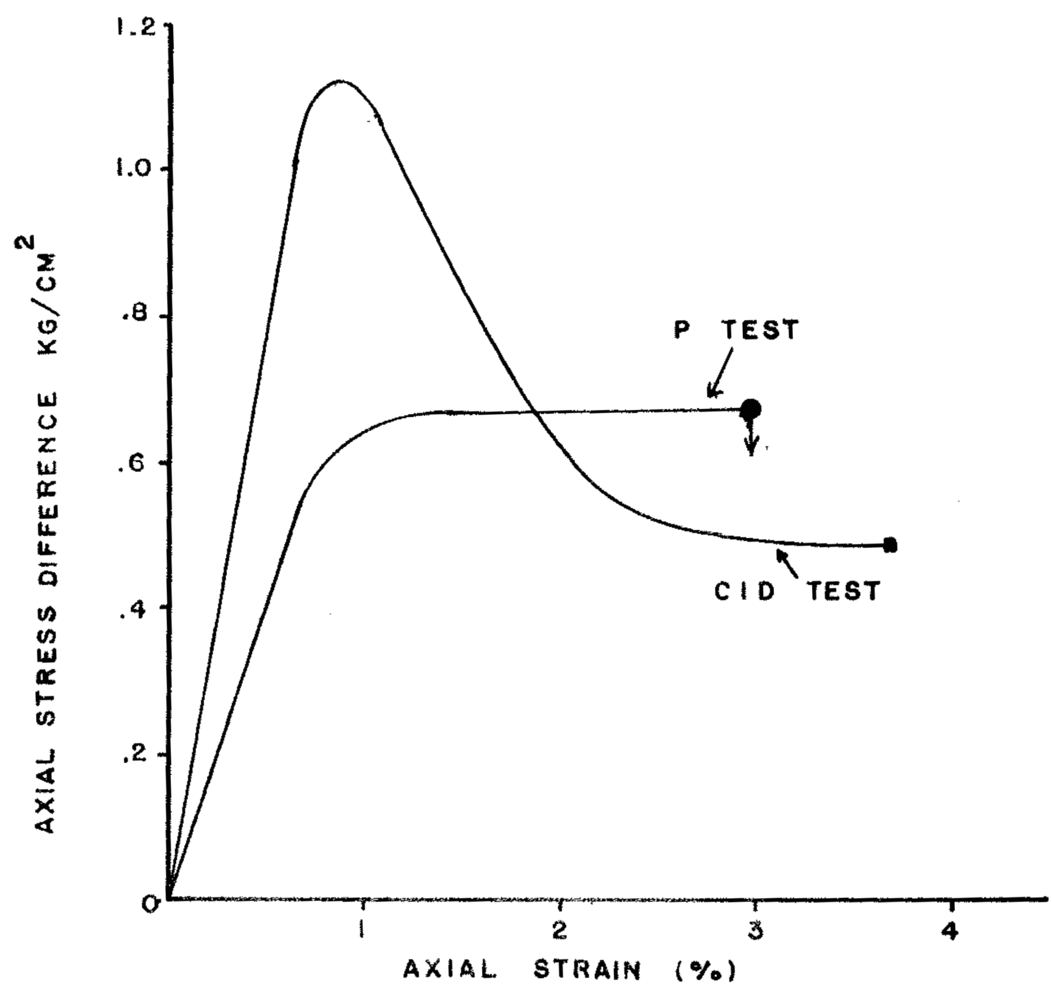

FIGURE 4.3 TYPICAL STRESS - STRAIN CURVE

A) CID TEST (LEFEBVRE AND LAROCHELLE 1974)

B) P TEST (MITCHELL 1970)

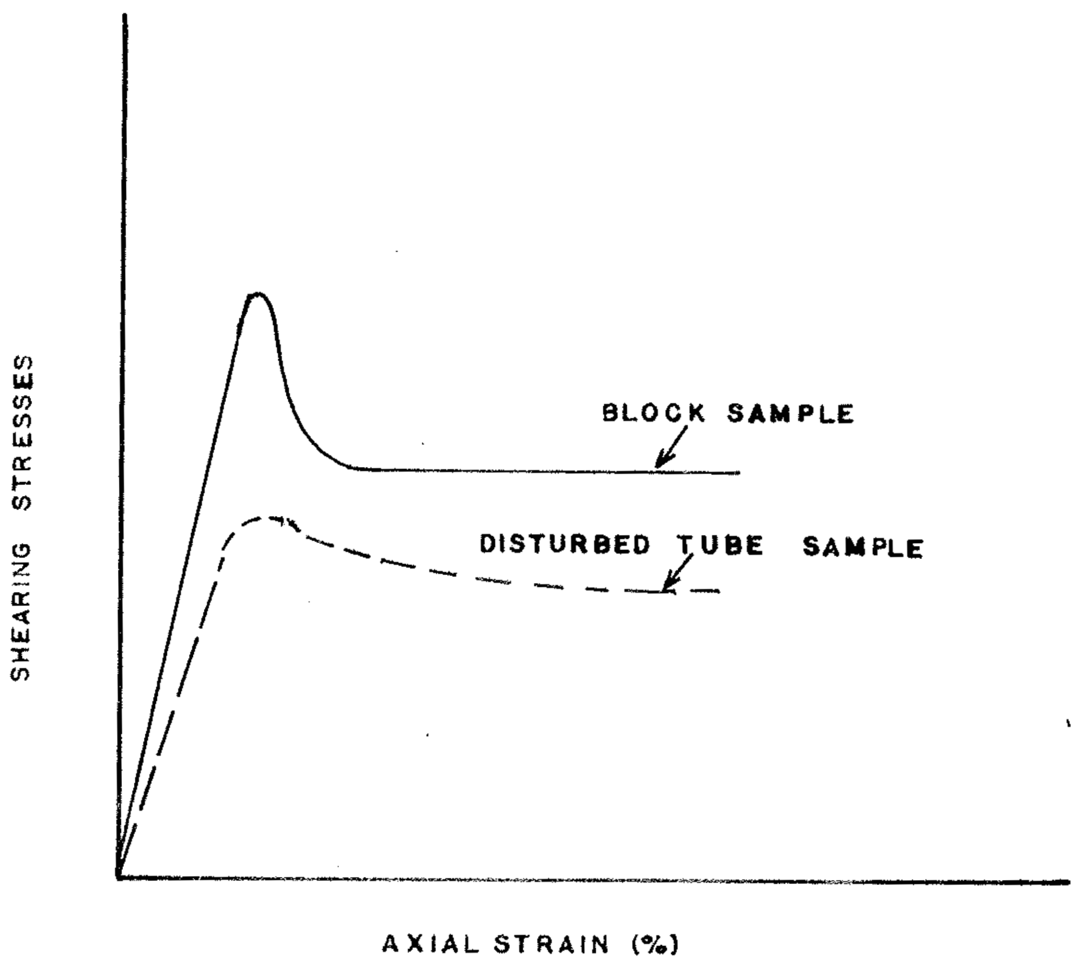

FIGURE 4.4 STRESS-STRAIN CURVES SHOWING SAMPLE DISTURBANCE (LAROCHELLE AND LEFEBVRE 1971)

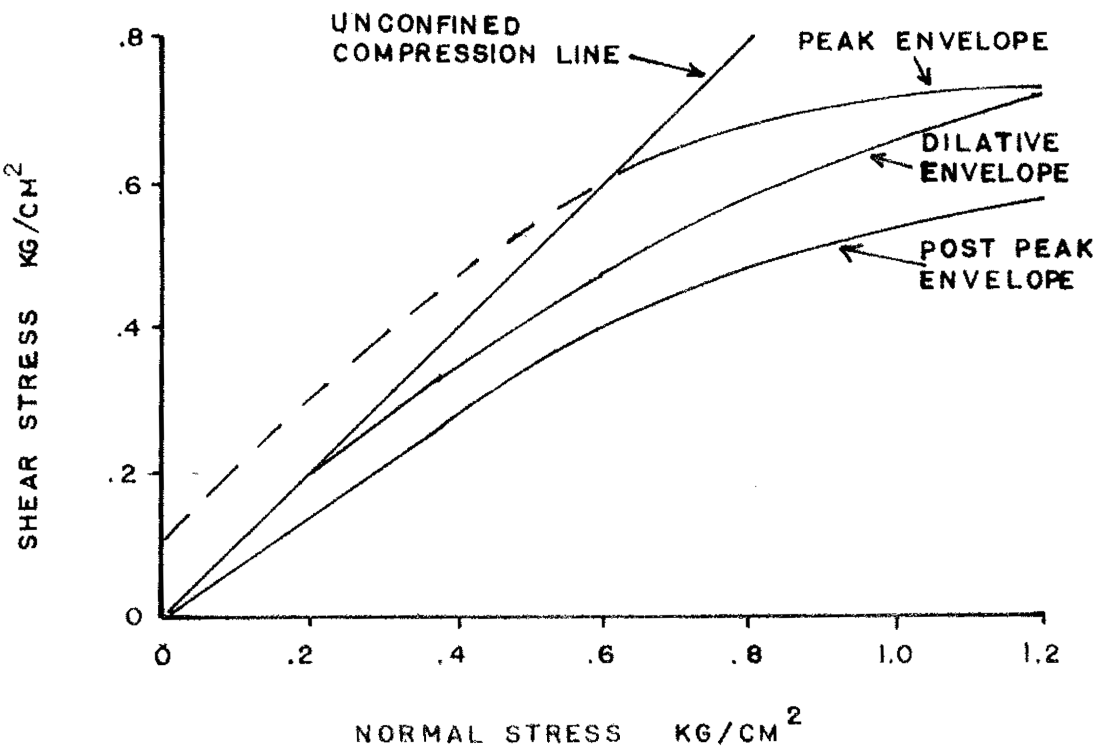

FIGURE 4.5 STRENGTH ENVELOPE (MITCHELL 1974)

CHAPTER V

UNRESOLVED PROBLEMS

5.1 Introduction

When dealing with the Champlain sea sediments, there are many problems that have to be contended with. We have so far discussed the principal ones. However, there are a few more which have a direct bearing on slope stability. They will be explored in this chapter. Measurement of sensitivity, sampling techniques, causes of microfissures, causes of slides, undrained shear strength measurement and $\phi = 0$ analysis are some examples of these problems.

5.2 Measurement of Sensitivity

It is generally agreed today that the measurement of sensitivity is highly dependent on the method used to measure it. Eden and Kubota (1961) investigated the four types of methods used to measure sensitivity of a clay soil. These are: the field vane, the unconfined compression test, the laboratory vane, and the fall cone test. The study found that no one method is to to be preferred over another. However, the field vane method is probably the most economical, but it appears to underestimate sensitivity at low liquidity indices and overestimate sensitivity when the liquid indices are high. They also concluded that no critical values of sensitivity have appeared that would distinguish a clay subject to earthflows and one that is not.

5.3 Sampling Techniques

Sampling is an important problem in these sensitive brittle Champlain clays. It is regarded as of minor importance in the fissured clays (Mitchell and Lawrence 1973) but is of major importance in the more intact clays. The effect of sampling on laboratory testing has been reported by many (Coates and McRostie 1963; Crawford 1963; LaRochelle and Lefebvre 1971; Raymond et al. 1971; Raymond 1973).

However good samples are a function of economics and practicality. Samples should only be as good as they need to be for a particular investigation. Coates and McRostie (1963) found that the effects of sample disturbance was quite important compared to size of sample. It would seem that large undisturbed block samples are the only samples that can be relied upon consistently (Coates and McRostie 1963; Crawford 1963; Eden 1970; LaRochelle and Lefebvre 1971; Raymond et al. 1971; Raymond 1973). Most investigations support the opinion that lateral strains allowed or induced by the sampler leads to serious disturbance.

LaRochelle and Lefebvre (1971) have shown that results from CID or CIU tests at low stress levels are affected appreciably by tube sampling. The stress-strain curve obtained from tube samples is considerably dampened compared to the peaked stress-strain behaviour obtained from block samples (see Figure 4.4). This is probably a direct result of the straining suffered by the sample on the introduction of the sampler into the ground. Raymond et al (1971) also found that extraction from tubes, without first cutting them in lengths of about 6 inches long, caused extensive disturbance.

Raymond et al. (1971) and Raymond (1973) after an extensive testing program have listed the sampling techniques in order of increasing disturbance: block samples, Osterberg samples, Swedish piston sampling, shelby piston with sharp cutting edge, shelby piston sampling, shelby open tube sampling.

5.4 Causes of Microfissures

An understanding of the causes and distribution of microfissures may lead to a recognition of the conditions essential for flow type slides (Mitchell 1970 (a)). There have been a few attempts that have tried to establish the causes of microfissures, but most so far are just speculation.

Stress relief is probably the most quoted cause of microfissures (Eden and Mitchell 1970; Mitchell 1970 (a)). This mechanism would be dependent on the relationship between swelling pressure and cementation bond of the clay.

A second possible cause of microfissuring could be the fatiguing effect of seasonal change with respect to temperature and groundwater (Mitchell 1970). It is a well known fact that the drying and wetting cycle in Champlain clay produces irrecoverable deformations (Warkentin and Bozozuk 1970). Does this phenomenon also cause a system of jointing? Sangrey and Paul (1971) discount the idea that microfissuring is caused by dessication or frost action because the microfissures are not continuous but en echelon; they interlock.

5.5 Causes of Slides

Water infiltration in the mass is considered to be the instigator of most slides. Extended periods of groundwater pressure may result in sufficient strain to develop tension cracks near the top of a slope. Complete failure may depend on the availability of surface water entering via tension cracks (Eden and Mitchell 1970, 1973).

LaRochelle (1972) reports an upward gradient at St. Louis de Yamaska affecting the toe of the slope. The flow regime is controlled by the topography of the underlying bedrock.

The importance of knowing accurately the groundwater condition at a site has been stressed in previous discussions. Groundwater fluctuation and movement are now considered the principal causes of landslides in Champlain clays.

A second important cause of slope failure is toe erosion. We may notice in Table 3.1 that most slides occur along major rivers where active toe erosion is sometimes present (Karrow 1972; Eden and Mitchell 1973).

However, there may be some unknown causes of landslides in Champlain clays which have not yet been accounted for. It is not until we have reached a complete chemical and hydro-chemical knowledge of the cementation bonds and a complete understanding of the behaviour of the clay mass that speculation will stop with regards to causes of landslides in this material.

5.6 Undrained Shear Strength Measurement and $\phi = 0$ Analysis

So far we have not discussed short term stability. It is however very important. We shall offer here only a brief discussion of the problems involved in utilizing the short-term stability analysis.

There are basically two ways of measuring the undrained shear strength of a material: laboratory methods and in situ probings.

Laboratory methods (i.e. unconfined compression, laboratory vane) are subjected to sample disturbances as previously discussed. LaRochelle and Lefebvre (1971) and Eden (1970) report values of undrained shear strength obtained from tube samples 50 to 60 percent smaller than values obtained from block samples.

There are three in situ methods available: vane, pressuremeter, penetrometer. The vane is by far the most widely used method. However, if we compare vane test measurements with values of undrained shear strength obtained from an unconfined compression test on block samples, we notice that the vane strengths are about 30 percent smaller (LaRochelle and Lefebvre 1971). According to these authors this reduction can be explained by two causes: straining due to the introduction of the vane and progressive failure. An attempt by LaRochelle et al. (1973) to extrapolate to zero blade thickness using vanes of different thicknesses only increases the undrained shear strength by about 15 percent. Hence, there is a possibility of progressive failure.

The two other methods of measuring undrained shear strength are still in the experimental stage. The pressure-meter is hampered by the technique used to obtain the cavity in which the probe is lodged (LaRochelle et al. 1973). Ladanyi (1972) lists various advantages in using the pressuremeter: soil is less disturbed, natural planes of weakness do not much affect the test. The penetrometer has the same advantages as the pressuremeter but a reliable value of E/Cu must be obtained before it can be used with confidence. However, the rate effect of testing must be determined for both methods. This effect could well explain part of the discrepancy between the measurements of undrained shear strengths.

The use of $\phi = 0$ or short term analysis has not received much attention by researchers. It has been previously mentioned that the vane strength underestimates the undrained shear strength obtained form block samples by about 30 percent. However, field experiences with large-scale tests prove that the vane strength overestimates the factor of safety (LaRochelle et al. 1974). Bjerrum (1972) has suggested an empirical approach whereby a correction factor of a magnitude dependent on the plasticity of the clay is applied to the vane strength. Rate effects and anisotropy are considered the main causes for this reduction in strength. Where the clays are microfissured or even cracked, the vane strengths are again much too high. It is believed that stress relief and the presence of fissures hasten the dissipation of the negative pore pressures and hence create instability quickly after excavation (Bazett et al. 1961; Lo et al. 1969; Lo 1970). Again last year several workers, in Templeton, Quebec, were buried alive when the sloped trench they were working in, failed.

5.7 Conclusion

In essence there are still quite a few problems left to be resolved before geotechnical work in Champlain clays may be attempted in all confidence.

Stability of natural slopes is an extensive problem in this relatively young topography. The worst conditions for instability are:

- very dry summers (opening tension cracks) followed by a wet autumn

- very heavy snowfall followed by slow spring melting permitting maximum infiltration
- a very wet spring

There is no doubt that the presence of high groundwater is a sure sign of trouble.

CHAPTER VI

CONCLUSION

6.1 Prediction of Further Catastrophes

To the layman it would seem that catastrophes such as St. Jean Vianney should be easy to predict. This is not the case. Slides in Champlain clays give very little warning; only a few tension cracks prior to failure.

The work done by Mitchell and Markwell (1974) is a step in the right direction. The general stability or instability of an area can be assessed quickly in the manner that they proposed. There are however thousands of miles of shorelines along rivers dissecting the Champlain sea deposit. It is an impossible task to evaluate the stability of the shoreline everywhere.

Karrow (1972) suggests that location of landslide scars should be mapped, pointing out that these areas are very susceptible to further activity. A prime example is St. Jean Vianney. Where there have been no earthflows the hazard is less but not non-existant.

6.2 Control Considerations

Creep movement opening tension cracks in the Outaouais area is an ever present possibility (Mitchell and Eden 1972). These would permit the infiltration of runoff water which builds up groundwater pressure bringing closer the onset of failure. Cracks at the crest of a slope should obviously be sealed with the briefest possible delay (Eden and Mitchell 1973).

Since water is the main problem of slope instability, toe drains should be beneficial. Their presence should assure that no build-up of pore pressure is created during the wet season of the year. The critical pore pressure parameter must be evaluated analytically to whatever factor of safety the slope is designed for.

The protection of slope toes actively being eroded by a river is another preventative measure that may be used to prevent slides in Champlain clays.

The use of slope flattening is not a method that is favoured. If stress relief is the cause of microfissuring then flattening a slope may create worse long-term stability than that existing before.

6.3 State of Evaluating Long-Term Stability

Ever since geotechnical engineers realised that slope failures in the Champlain clay were initially a shallow feature, the use of low confining pressures in drained triaxial tests to simulate low stresses in the field has proven to be one of the most important advancements in the research on slope failures in Champlain clay. This phase of the failure envelope has a high effective friction angle and a very low effective cohesion. The use of either the dilative/frictional concept or the concept of progressive failure is still a debatable issue.

However, it is believed that the dilative failure envelope is theoretically and conceptually correct in the Outaouais area. It is also suspected that this theory is applicable to the St. Lawrence clays. More research is necessary to confirm this hypothesis. The practicality of using the post-peak failure criteria may be of great value. The degree of conservatism in using this theory compared to the dilative approach must be determined before it is abandoned.

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